3

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OVERVIEW

This chapter deals with the industrial process source categories described in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC Guidelines). Good practice guidance* is provided for major emissions source categories – including: Cement production, lime production, iron and steel industry, adipic acid and nitric acid production, aluminium production, magnesium production, sulfur hexafluoride (SF_6) emissions from electrical equipment, and from other sources, perfluorocarbons (PFC), hydrofluorocarbons (HFC) and SF_6 emissions from semiconductor manufacturing, emissions of substitutes for ozone depleting substances (ODS substitutes) including seven sub-source categories, and HCFC-22 manufacture.

Good practice guidance has not yet been developed for the following source categories described in the *IPCC Guidelines*, Chapter 2, Industrial Processes: limestone and dolomite use (including use in the iron and steel industry), soda ash production and use, production and use of miscellaneous mineral products, ammonia production, carbide production, production of other chemicals, ferroalloys, CO_2 emissions from aluminium, other metal production, SF_6 used in aluminium and magnesium foundries; pulp and paper industries; and food and drink industries. Inventory agencies should of course continue to use the *IPCC Guidelines* for these source categories. The cross-cutting parts of the *good practice guidance* in Chapters 6 to 8, and the Annexes can also be applied to those source categories.

According to the *IPCC Guidelines* all emissions of HFCs, PFCs and SF_6 – including those occurring in non-industry sectors – should be included in the Industrial Processes Sector (see guidance described in Sections 3.3 to 3.8). The ‘amount of destruction’ should be considered in each emission equation. At present, there are few practices of treatments that destroy HFCs, PFCs, or SF_6. However, in the future, destruction treatments may be developed in order to reduce emissions.

To improve clarity in this chapter sometimes tier numbers are introduced as alternative names for methods that are described in the *IPCC Guidelines* but not numbered. Further, additional tiers have in some cases been described through the process of defining *good practice guidance* for a particular source category. For the industrial process source categories, the tiered approach as described in the sections and the decision trees should be interpreted as follows (see the guidance in Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories).

- If the source category is not a *key source category*, but the data and resources of the inventory agency allow an emission calculation to be performed with Tier 2 or higher methods, the inventory agency is, of course, encouraged to do so (instead of applying the Tier 1 approach).
- If the source category is a *key source category*, but the inventory agency is unable to collect the data and use the method (or tier) suggested for *good practice*, it is considered *good practice* to use the Tier 1 method for the emission calculation and document the reason for using that method.

3.1 CO_2 EMISSIONS FROM INDUSTRY

In the *IPCC Guidelines*, Vol. 3, Section 2.1, Industrial Processes Overview, the separation of feedstock and energy uses and the identification of any fuel by-products from processes have been identified as a particularly difficult area of energy statistics. To avoid double-counting or omissions of carbon dioxide (CO_2), the compilers of energy and industry-related emissions should cooperate closely and compare their basic fuel use data. Close cooperation is particularly important for the iron and steel industry where, according to the *IPCC Guidelines*, coke (or coal) consumption is considered to be industrial, since the primary purpose of coke (or coal) oxidisation is to produce pig iron, not to produce process heat. Another possible area of double-counting is 'CO_2 emissions from the use of limestone and dolomite' that should be accounted for in its specific section (*IPCC Guidelines*, Vol. 3, Section 2.5, Limestone and Dolomite Use), not in the other Industrial Processes source categories of the *IPCC Guidelines* where usage is mentioned, such as in the Iron and Steel Sub-source Category.

3.1.1 Cement production

3.1.1.1 Methodological issues

Emissions of CO_2 occur during the production of *clinker* that is an intermediate component in the cement manufacturing process. During the production of clinker, limestone, which is mainly (95%) calcium carbonate ($CaCO_3$), is heated (calcined) to produce lime (CaO) and CO_2 as a by-product. The CaO then reacts with silica, aluminium, and iron oxides in the raw materials to make the clinker minerals (that are dominantly hydraulic calcium silicates) but these reactions do not emit further CO_2. The main challenge in the estimation of CO_2 emissions from cement production is to overcome the difficulty that both the fraction of clinker in cement and CaO content in clinker may vary.

CHOICE OF METHOD

The decision tree in Figure 3.1, Decision Tree for Estimation of CO_2 Emissions from Cement Production, describes *good practice* in choosing the most appropriate method. As CO_2 emissions occur during the intermediate production of clinker, *good practice* is to estimate CO_2 emissions using data for clinker production and the CaO content of the clinker and correct for the loss of so-called Cement Kiln Dust (CKD) (Tier 2). If it is not possible to obtain clinker production data directly, clinker production should be inferred from cement production and a correction for clinker import and export statistics should be applied (Tier 1). Once an estimate of clinker production has been derived, the Tier 1 method estimates CO_2 emissions through a process similar to Tier 2. The simple method described in the *IPCC Guidelines* to multiply a default cement-based emission factor by cement production, without correction for import/export of clinker, is not considered to be a *good practice* method.

Tier 2 Method: Use of clinker production data

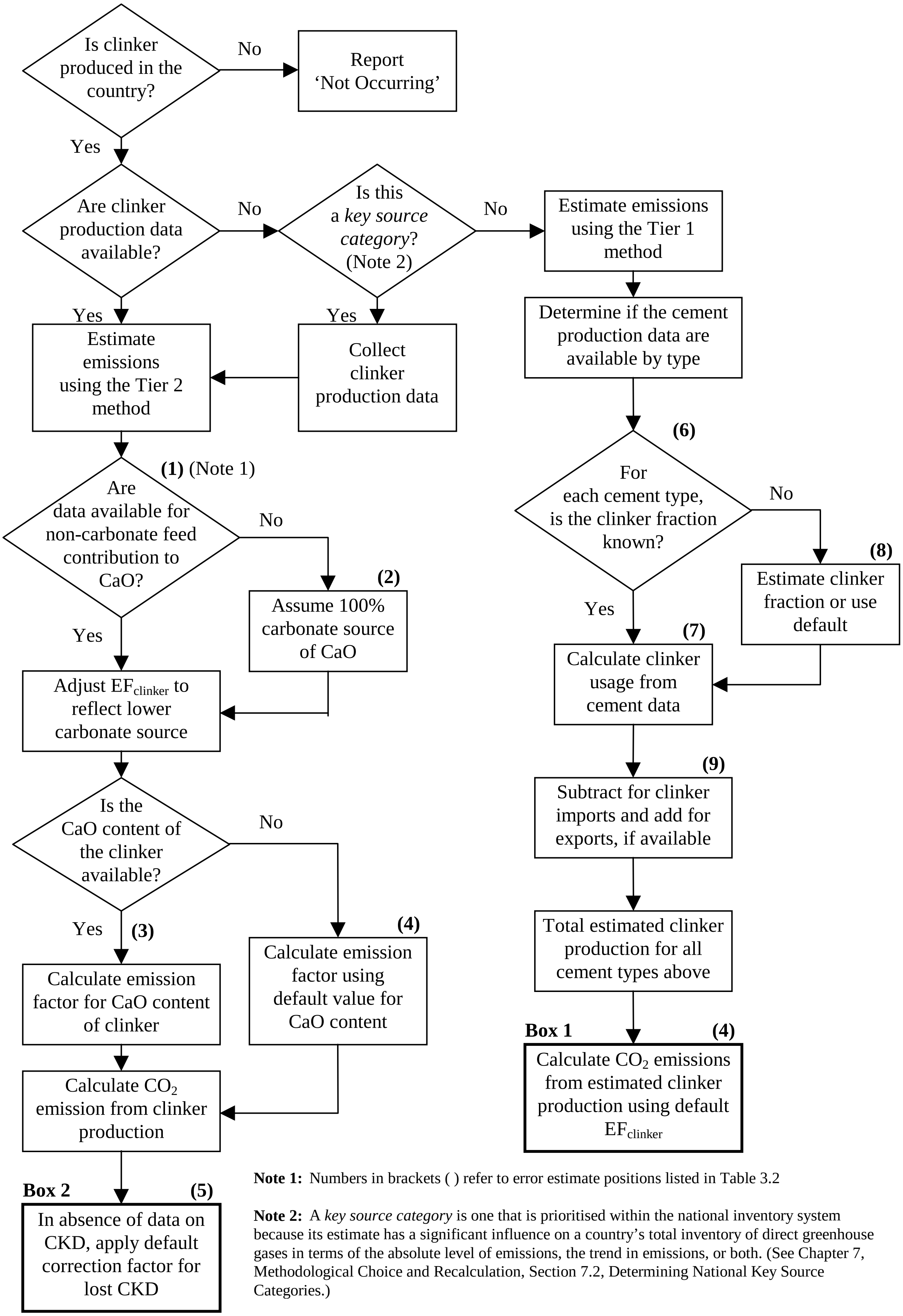
The most rigorous *good practice* method is to use aggregated plant or national clinker production data and data on the CaO content in clinker, expressed as an emission factor (EF), following Equation 3.1:

EQUATION 3.1

$$\text{Emissions} = EF_{\text{clinker}} \bullet \text{Clinker Production} \bullet \text{CKD Correction Factor}$$

This approach assumes that all of the CaO is from a carbonate source (e.g. $CaCO_3$ in limestone). If data on non-carbonate sources are available, an adjustment (decrease) should be made to the emission factor EF_{clinker}.

Figure 3.1 Decision Tree for Estimation of CO_2 Emissions from Cement Production



Note 1: Numbers in brackets ( ) refer to error estimate positions listed in Table 3.2

Note 2: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Cement Kiln Dust (CKD) is non-calcined to fully calcined dust produced in the kiln.[1] CKD may be partly or completely recycled to the kiln. Any CKD that is not recycled can be considered lost to the system in terms of CO_2 emissions. *Good practice* is to correct for the CO_2 contained in non-recycled (lost) calcined CKD because this CO_2 will not be accounted for by the clinker produced. The amount of CO_2 lost can vary, but would range typically from about 1.5% for a modern plant to about 8% for a plant losing a lot of highly calcinated CKD (van Oss, 1998). As data on CKD are very scarce, the default CKD correction factor is 1.02 (i.e. to add 2% to the CO_2 calculated for clinker). If no calcined CKD is believed to be lost to the system, the correction factor will be 1.00 (van Oss, 1998).

Tier 1 Method: Use of cement production data

As mentioned above, calculating CO_2 emissions directly from cement production (i.e. using a fixed cement-based emission factor) is not consistent with *good practice*. Instead, in the absence of national clinker production data, cement production data may be used to estimate clinker production taking into account the types of cement produced and including a correction for international clinker trade (exports, imports), where relevant, as shown in Equation 3.2:

EQUATION 3.2

$$\begin{aligned}\text{Estimated Clinker Production} = {} & \text{Cement Production} \bullet \text{Clinker Fraction} \\ & - \text{Imported Clinker} + \text{Exported Clinker}\end{aligned}$$

If readily available, plant-specific data for the clinker fraction should be collected, otherwise a default clinker fraction can be used. If cement production cannot be disaggregated by type and it is suspected that both blended and portland cement types are being produced, it is *good practice* to assume a clinker fraction of 75%. If the cement production is known to be essentially all portland cement, then it is *good practice* to use a default value of 95% clinker. The default value of 98.3% clinker fraction suggested in the *IPCC Guidelines* is too high.[2]

CHOICE OF EMISSION FACTORS

Both Tier 1 and Tier 2 require emission factors for clinker that are based on stoichiometry, as shown in Equation 3.3:

EQUATION 3.3

$$EF_{clinker} = 0.785 \bullet \text{CaO Content (Weight Fraction) in Clinker}$$

The multiplication factor (0.785) is the molecular weight ratio of CO_2 to CaO in the raw material mineral calcite ($CaCO_3$), from which most or all the CaO in clinker is derived. The CaO content can vary somewhat by country and by facility.

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[1] To some extent, all cement kilns produce Cement Kiln Dust that is largely a mix of calcined and uncalcined raw materials and clinker. There are few data available on total CKD production, composition or disposition; these are functions of plant technologies and can vary over time. In general, the amount of CKD produced can be estimated as equivalent to about 1.5-2.0% of the weight of clinker production (van Oss, 1998). CKD can be directly recycled, or it may be recovered via electrostatic precipitation or filtration (baghouses) from the exhaust stacks (it would be vented to the atmosphere only at basic plants in developing countries). The recovered CKD may be recycled to the kiln as a raw material, used for other purposes, or transferred to a landfill. The degree of return to the kiln can be limited by the fact that CKD tends to accumulate contaminants such as alkalis. Any CKD not recycled to the kiln is 'lost' to the cement system in terms of CO_2 emissions. The calcined, or partially calcined, carbonate fraction of the lost CKD represents a generation of calcination CO_2 that is not accounted for by the amount of clinker produced. For a developed country operating modern plants with moderate recycling of CKD to the kilns, this extra CO_2 is probably equivalent to about 1.5-2.0% of the CO_2 calculated for clinker (van Oss, 1998). For plants doing little recycling, the percentage would be somewhat higher (e.g. 3%), and if the lost CKD is mostly calcined material, the extra CO_2 could range higher still (e.g. 6-8%). For most countries, the practical maximum extra CO_2 is unlikely to exceed 5% of the clinker CO_2 (van Oss, 1998).

[2] This ratio was calculated from the default CaO content in cement (63.5%) and the default CaO fraction in clinker (64.6%), and results in a clinker-cement ratio higher than the ratio for most pure portland cements.

Tier 2 Method

In using the Tier 2 method, it is *good practice* to estimate the CaO content in clinker by collecting data from individual plants or companies. Generally, the average CaO content of clinker does not change significantly on an annual basis, so an estimate can be developed periodically (e.g. every 5 years) in each country.[3] In the event that country-specific data cannot be obtained for the CaO content, a default weight fraction of 0.65 can be used (see the *IPCC Guidelines*, Vol.3, Section 2.3, Cement Production).[4]

Equation 3.3 is based on the assumption that all the CaO in clinker is from $CaCO_3$. Limestone and related carbonate materials are the major source of CaO for clinker, but there may be additional CaO sources (e.g. ferrous slag feeds) for some plants. This assumption will generally produce only a small error at most, but if it is known that other sources of CaO are being used as kiln feed in substantial amounts, the CaO contribution of these non-carbonate feeds should be subtracted from the clinker. However, quantitative data on raw materials consumed for clinker production generally will be lacking.

Tier 1 Method

In Tier 1, it is *good practice* to use the same default CaO content of 65% as in Tier 2, resulting in an emission factor of 0.51 tonne CO_2 per tonne of clinker. However, if sufficient data on CaO content of clinker are available, the CO_2 emission factor should be estimated as described for Tier 2 (see Figure 3.1, Decision Tree for Estimation of CO_2 Emissions from Cement Production).

CHOICE OF ACTIVITY DATA

Tier 2 Method: Clinker production data

The goal of collecting activity data for this source category is to arrive at a value for clinker production. *Good practice* is to collect clinker production data directly from national statistics or preferably from individual plants. Plant data may include information on the CaO content of the clinker and possibly non-carbonate sources of CaO.

Tier 1 Method: Cement production data

If national clinker production data are not readily available and cannot be collected, the preferred alternative is to estimate clinker production from cement production data. This requires country-specific knowledge of cement production as well as cement and clinker composition. To use cement production and assume a default clinker fraction may introduce significant error in the emission calculation.

Several issues should be considered when estimating clinker production.

First, the choice between top-down and bottom-up data collection is important.[5] Collecting data from individual producers rather than using national totals will increase the accuracy of the estimate, because these data will account for variations in conditions at the plant level. This is particularly important for determining possible differences in cement composition and irregularities in annual production (i.e. using clinker feedstock instead of production at various times).

Second, the clinker content in cement and the CaO content in clinker should be considered. It is *good practice* to collect cement production data broken down by cement type because each type of cement will contain a different proportion of clinker. The clinker fraction varies among countries and care must be taken to ensure that it is consistent with the local definition of the types of cement (see Table 3.1, Percent Clinker in the Cement Production Mix, Table 3.3A, Examples of Clinker Fraction of Blended Cement ‘Recipes’ (Based on US Standards), and Table 3.3B, Classification of Cement Types (Based on European Standards (DIN 1164, part 1))). Determining the types of cement that are being produced or included in cement production data is of critical importance because a number of cement types other than common portland cement may be included in cement statistics. These cement types may have widely different clinker fractions. There may be variations in the CaO content of clinker for various types of cement produced but, for a given cement type, the CaO content of clinker

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[3] The average CaO content for clinker used in a country is the weighted average of the CaO contents of the clinker from various plants with the inferred production levels (i.e. multiplied by their CKD correction factor) being the weights. This average for the country should be reported for comparison and QA/QC purposes.

[4] Although the CaO content for a specific cement type will generally be closely controlled (to within 1-3%) by the plant, the CaO content of clinker may vary with the type of cement produced.

[5] In the context of cement production this means country-level versus plant-level accounting.

is likely to remain fairly constant from year to year. If plant-level data are available for both the clinker fraction and the CaO content, these data can be used to arrive either at a plant average or a country average.

Third, if cement production cannot be disaggregated by type and the clinker fraction in cement cannot be estimated reliably, default values for the clinker/cement ratio and its CaO fraction may be used. As shown in Table 3.1, Percent Clinker in the Cement Production Mix, the default value of 98.3% in the *IPCC Guidelines* will generally lead to an overestimation of CO_2 emissions. Many inventory agencies report hydraulic cement production data, but this term can include several types of cement and the assumption of 100% portland cement production may result in overestimates. The clinker fraction can range from a high of 95-97% for a straight portland cement, to 25% or less for a slag cement (see Table 3.3A, Examples of Clinker Fraction of Blended Cement 'Recipes' (Based on US Standards), and Table 3.3B, Classification of Cement Types (Based on European Standards (DIN 1164, part 1))). Therefore, if cement production cannot be disaggregated by type, and it is suspected that both blended and portland cements are being produced, it is *good practice* to assume a clinker fraction of 75%. If the cement production is known to be essentially all portland cement, *good practice* is to use a default value of 95% clinker. In either case, the default clinker is assumed to have a 65% CaO fraction.

TABLE 3.1
PERCENT CLINKER IN THE CEMENT PRODUCTION MIX

Country Production Mix (PC/blend)[a]	**Percent Additives (Pozzolan + Slag) in the Blended Cement**[b]				
	10%	**20%**	**30%**	**40%**	**75%**
0/100	85	76	66	57	24
15/85	87	79	71	63	26
25/75	88	81	74	66	42
30/70	88	82	75	68	45
40/60	89	84	78	72	52
50/50	90	85	81	76	60
60/40	91	87	84	80	66
70/30	92	89	86	84	74
75/25	93	90	88	85	77
85/15	94	92	91	89	84
100/0	Straight Portland cement having 95% clinker fraction				

[a] Country production mix refers to the range of products of a country, e.g. '75/25' means 75% of total production is portland and the rest is blended. It is assumed that all the hydraulic cement is portland or blended or both, or pure pozzolan. Masonry would approximate a product mix of 60/40 to 70/30 portland/blended, for the 75% additive column. Other hydraulic cements (e.g. aluminous) are assumed to be nil.

[b] The inclusion of slag allows for a base to the blend of portland or portland blast furnace slag cement or both. All portland in blended cement is assumed to be 95% clinker. Values calculated as: % PC • 95% + % Blend • [100 – additive %] • 95%.

Source: Calculated by van Oss (1998).

COMPLETENESS

Clinker production plants are generally large and well known in each country. As a result, clinker production data may be available in national statistical databases, or could be easily collected, even if such data have not been published in national statistics. Cement or clinker production data from national statistics may not be complete in some countries where a substantial part of production comes from numerous small kilns, particularly vertical shaft kilns, for which data are difficult to obtain.

DEVELOPING A CONSISTENT TIME SERIES

It is *good practice* to calculate emissions from clinker production using the same method for every year in the time series. Where data are unavailable to support a more rigorous method for all years in the time series, *good practice* is to recalculate these gaps according to the guidance provided in Chapter 7, Methodological Choice and Recalculation.

UNCERTAINTY ASSESSMENT

If clinker data are available, the uncertainty of the emission factor is equal to the uncertainty of the CaO fraction and the assumption that it was all derived from $CaCO_3$. Since chemical analysis has an uncertainty of 1-2%, this is also the uncertainty of the emission factor. The uncertainty in clinker production data is about 1-2%. If clinker production must be estimated from cement production, the error is about 35%, Table 3.2, Example of Estimation of Uncertainties in CO_2 Emission Calculations Based on the Steps in Figure 3.1. As an example, an attempt has been made to estimate errors at individual steps during emissions estimates (see Figure 3.1, Decision Tree for Estimation of CO_2 Emissions from Cement Production, numbers (1)-(9)). The results are presented in Table 3.2 and give an indication as to how large an error is introduced when different tiers are used.

The component uncertainties in Table 3.2 below have been combined as though they were symmetric maximum-minimum errors. This approach was adopted because many of the uncertainties are non-Gaussian, and some may be systematic. The conclusion from the analysis is that estimation of emissions via cement production data results in an error not exceeding 20 to 40% (depending on the view taken about the values in Table 3.2 where ranges are quoted). Estimation via direct clinker production data decreases the error to about 10%. These ranges should be treated as systematic errors when applying the methods outlined in Chapter 6, Quantifying Uncertainties in Practice.

TABLE 3.2
EXAMPLE OF ESTIMATION OF UNCERTAINTIES IN CO_2 EMISSION CALCULATIONS OF CEMENT PRODUCTION BASED ON THE STEPS IN FIGURE 3.1

Step	Error[a]	Comment	Method
(1)	1-2%	Uncertainty of plant-level production data. Plants generally do not weigh clinker better than this. Assumes complete reporting.	Tier 2
(2)	1-3%	Error associated with assuming that all CaO in clinker is from calcium carbonate.	Tier 2
(3)	1-2%	Uncertainty of plant-level data on CaO content of clinker. This is the best case error of chemical analysis on a production basis.	Tier 2
(4)	4-8%	Error in assuming an average CaO in clinker of 65% (CaO usually 60-67%).	Tier 1, 2
(5)	5%	The best case error assuming that weight and composition of cement kiln dust (CKD) are known.	Tier 2
(6)	1-2%	Plants generally do not weigh cement production better than this. Assumes complete reporting.	Tier 1
(7)	20%	Error due to miss-reporting or non-unique blended cement formulations.	Tier 1
(8)	35%	‘Worst case’ assumes overall 70% blended cement of 50% non-clinker recipe.	Tier 1
(9)	5%	Reporting error, but more accurate than for cement (clinker tariff number is less encompassing).	Tier 1
Summary of resulting error estimates in emissions (see Chapter 6, Quantifying Uncertainties in Practice)			
	20-40%	**Tier 1 error** assuming that clinker production data were derived from cement production data (excluding additional errors for correction of international clinker trade stemming from any need to estimate national clinker production level from cement production).	
	5-10%	**Tier 2 error** assuming derivation from clinker production data.	

[a] Numbers refer to Figure 3.1 and are the ‘maximum’ error – i.e. the most likely rectangular distribution function is assumed. The estimated error at each step, and certain summations thereof, are based on experience in collecting and calculating data.

Source: van Oss (1998).

3.1.1.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving. Some examples of specific documentation and reporting relevant to this source category are provided below:

Tier 2 Method

For Tier 2, this includes the following data:

(i) Clinker production and CaO content of clinker;

(ii) Data on non-carbonate feeds to kiln;

(iii) Cement kiln dust losses (indicate if default values were used).

Tier 1 Method

For Tier 1, this includes the following data:

(i) Cement production by type;

(ii) Clinker import/exports;

(iii) Clinker/cement ratio by type of cement (indicate if default values were used);

(iv) CaO content of clinker (indicate if default values were used);

(v) Cement kiln dust losses (indicate if default values were used).

In addition, for both tiers, inventory agencies should:

(i) Clearly specify which data have been used: IPCC defaults or country-specific data;

(ii) Provide all information needed to reproduce the estimate, and provide documentation of QA/QC procedures;

(iii) To preserve an internally consistent emission time series, whenever national methods change, recalculate the entire base-year emissions (from 1990 to the current year). This also calls for additional documentation and discussion of changes;

(iv) If confidentiality is an issue for any type of production, aggregate estimates to the minimum extent needed to maintain confidentiality.

Note: The calculation of CO_2 emissions from fuel combustion (*IPCC Guidelines*, Vol. 3, Chapter 1, Energy) should consider waste fuels in cement kilns (tyres, waste oils, paints etc.) that may not be included in the energy balance. These emissions are not to be mixed with the reporting of industrial process emissions.

3.1.1.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, Section 8.7, Source Category-specific QC Procedures (Tier 2), and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventories agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

In addition to the guidance in Chapter 8, specific procedures of relevance to this source category are outlined below.

Comparison of emissions estimates using different approaches

If the bottom-up approach is used to collect activity data, then inventory agencies should compare the emissions estimates to the estimates calculated using national production data for the cement or clinker industry (top-down approach). The results of such comparisons should be recorded for internal documentation, including explanations for any discrepancies.

Review of emission factors

Inventory agencies should compare aggregated national emission factors with the IPCC default factors in order to determine if the national factor is reasonable relative to the IPCC default. Differences between national factors and default factors should be explained and documented, particularly if they are representative of different circumstances.

If the aggregated top-down approach is used, but limited plant-specific data are available, inventory agencies should compare the site or plant level factors with the aggregated factor used for the national estimate. This will provide an indication of the reasonableness and the representativeness.

Site-specific activity data check

For site-specific data, inventory agencies should review inconsistencies between sites to establish whether they reflect errors, different measurement techniques, or result from real differences in emissions, operational conditions or technology. For cement production, inventory agencies should compare plant data (content of CaO in clinker, content of clinker in cement) with other plants.

Inventory agencies should ensure that emission factors and activity data are developed in accordance with internationally recognised and proven measurement methods. If the measurement practices fail this criterion, then the use of these emissions or activity data should be carefully evaluated, uncertainty estimates reconsidered and qualifications documented. If there is a high standard of measurement and QA/QC is in place at most sites, then the uncertainty of the emissions estimates may be revised downwards.

Expert review[6]

Inventory agencies should include key industrial trade organisations associated with cement and clinker production in a review process. This process should begin early in the inventory development process to provide input to the development and review of methods and data acquisition. Expert review is particularly important for the content of CaO in clinker, sources of CaO, differences in cement composition, and irregularities in annual production.

Third party reviews are also useful for this source category, particularly related to initial data collection, measurement work, transcription, calculation and documentation.

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[6] The types of expert reviews are covered in Chapter 8, Quality Assurance and Quality Control, and include peer review and third party reviews and audits. In this chapter, the term *expert review* is used to cover all aspects of review, including auditing.

APPENDIX 3.1.1A.1 DEFINITIONS OF CEMENT TYPES

Data for cement commonly include all forms of hydraulic cement, and may include varieties such as slag cement that do not involve substantial amounts of clinker and the associated release of CO_2 from calcination. Blended cements and slag or pozzolan cements are produced and used in many countries. Tables 3.3A, Examples of Clinker Fraction of Blended Cement 'Recipes' (Based on US Standards) and 3.3B, Classification of Cement Types (Based on European Standards (DIN 1164, part 1)), present data on some of the most common types of cement in the US and European countries, respectively.

TABLE 3.3A
EXAMPLES OF CLINKER FRACTION OF BLENDED CEMENT 'RECIPES' (BASED ON US STANDARDS)

Cement Name	Symbol	Recipe	% of Clinker	Notes
Portland	'PC'	100% PC	95-97	
Masonry	'MC'	2/3 PC	64	recipe varies considerably
Slag-modified portland	I(SM)	slag < 25%	>70-93	
Portland blast furnace slag	IS	slag 25-70%	28-70	
Portland pozzolan	IP and P	pozz 15-40%	28-79/81	base is PC or IS
Pozzolan-modified portland	I(PM)	pozz < 15%	28-93/95	base is PC or IS
Slag cement	S	slag 70%	<28/29	can use lime instead of clinker

Source: van Oss (1998) based on ASTM (1996a).

TABLE 3.3B
CLASSIFICATION OF CEMENT TYPES (BASED ON EUROPEAN STANDARDS (DIN 1164, PART 1))

Cement Name	Symbol	Recipe	% of Clinker
Portland cement	CEM I	–	95-97
Slag modified portland	CEM II/A-S	slag 6-20%	77-90
	CEM II/B-S	slag 21-35%	62-76
Portland pozzolan	CEM II/A-P	pozzolan 6-20%	77-90
	CEM II/B-P	pozzolan 21-35%	62-76
Portland fly ash cement	CEM II/A-V	fly ash 6-20%	77-90
Portland oil shale cement	CEM II/A-T	oil shale 6-20%	77-90
	CEM II/B-T	oil shale 21-35%	62-76
Portland limestone cement	CEM II/A-L	limestone 6-20%	77-90
Portland fly ash slag cement	CEM II/A-SV	fly ash 10-20%	77-86
	CEM II/B-SV	slag 10-21%	76-86
Portland blast furnace slag	CEM III/A	blast furnace slag 36-65%	34-61
	CEM III/B	blast furnace slag 66-80%	19-33

Source: DIN (1994).

Cement types can be characterised as follows:

- **Hydraulic cement**: any cement that sets and hardens in water.
- **Portland cement** is a mixture of clinker and gypsum, with clinker comprising about 95-97% of the total weight of the cement (95% clinker is a common default value). Many countries may allow a small (1-5%) addition of inert or cementitious extenders. Some production data for 'portland cement' may include blended cements.

- **Blended cements** are a mix (sometimes interground) of portland cement or its clinker, with additives such as ground granulated blast furnace slag and pozzolans (e.g. fly ash, silica fume, burned shale). The additives make up a variable, non-unique percentage of the total cement, but generally are in the range of 15-40%, with clinker thus making up 57-81%.
- **Slag cements** contain high proportions (> 70%) of ground granulated blast furnace slag, with the remainder either portland cement (or clinker) or lime or both. Some slag cements contain no portland cement at all. Granulated blast furnace slag is itself a latent cement (as binding material), possessing moderate hydraulic properties, but develops improved cementitious properties when interacted with free lime (and water).
- **Masonry cement** recipes vary but typically are about 2/3 portland cement or its clinker, and 1/3 additives such as lime or limestone.
- **Aluminous cements** are hydraulic cements manufactured by burning a mix of limestone and bauxite. Typically, aluminous cements contain about 30-42% CaO, or about 45-65% of the CaO content of portland cement clinker.
- **Pozzolan cement** can refer to a blended cement containing a substantial quantity of pozzolans, but more properly refers to a cement made predominantly of pozzolans and an activator agent – such as lime – that supplies CaO but does not involve substantial amounts of portland cement or portland cement clinker.
- **Pozzolan** is a siliceous material that in itself is not cementitious, but which develops hydraulic cement properties when it reacts with free lime (CaO) and water. Common examples of pozzolans include natural pozzolans (e.g. certain volcanic ashes or tuffs, certain diatomaceous earths, burned clays and shales) and synthetic pozzolans (e.g. silica fume, fly ash).

3.1.2 Lime production

3.1.2.1 Methodological issues

Lime production[7] emits CO_2 through the thermal decomposition (calcination) of the calcium carbonate ($CaCO_3$) in limestone to produce quicklime (CaO), or through the decomposition of dolomite[8] ($CaCO_3 \cdot MgCO_3$) to produce dolomitic 'quick' lime ($CaO \cdot MgO$). *Good practice* to estimate emissions from lime production is to determine the complete production of CaO and $CaO \cdot MgO$ from data on lime production. The accuracy depends on obtaining complete lime production statistics and establishing the proportion of different types of lime. The *IPCC Guidelines* address both points briefly, presenting an upper limit emission factor as a default to avoid underestimating emissions.

CHOICE OF METHOD

The *IPCC Guidelines* provide the following equation for estimating emissions:

EQUATION 3.4

$$CO_2 \text{ Emissions} = \text{Emission Factor (EF)} \bullet \text{Lime Production}$$

Where:

EF = 785 kg CO_2 per tonne of high calcium quicklime, and

913 kg CO_2 per tonne of dolomitic quicklime

Equation 3.4 can be applied either to national statistics or at the producer level. It is *good practice* to assess the available national statistics for completeness, and for the ratio of limestone to dolomite used in lime production. Industries that use lime, and may produce it, are listed in the section on completeness. Data collection should cover both the amounts produced and average composition. The choice of *good practice* methods depends on national circumstances (as shown in Figure 3.2, Decision Tree for Lime Production).

CHOICE OF EMISSION FACTORS

The default emission factors in the *IPCC Guidelines* mentioned under Equation 3.4 correspond to 100% of CaO (or $CaO \cdot MgO$) in lime (stoichiometric ratio) and can lead to an overestimation of emissions since the CaO and (if present) MgO content may be less than 100%. It is *good practice* to apply Equation 3.5A or Equation 3.5B, or both, to adjust the emission factors and to account for the CaO or the $CaO \cdot MgO$ content (see Table 3.4, Basic Parameters for the Calculation of Emission Factors for Lime Production):

EQUATION 3.5A

$$EF_1 = \text{Stoichiometric Ratio } (CO_2 / CaO) \bullet \text{CaO Content}$$

Where: EF_1 = emission factor for quicklime

EQUATION 3.5B

$$EF_2 = \text{Stoichiometric Ratio } (CO_2 / CaO \cdot MgO) \bullet (CaO \cdot MgO) \text{ Content}$$

Where: EF_2 = emission factor for dolomitic quicklime

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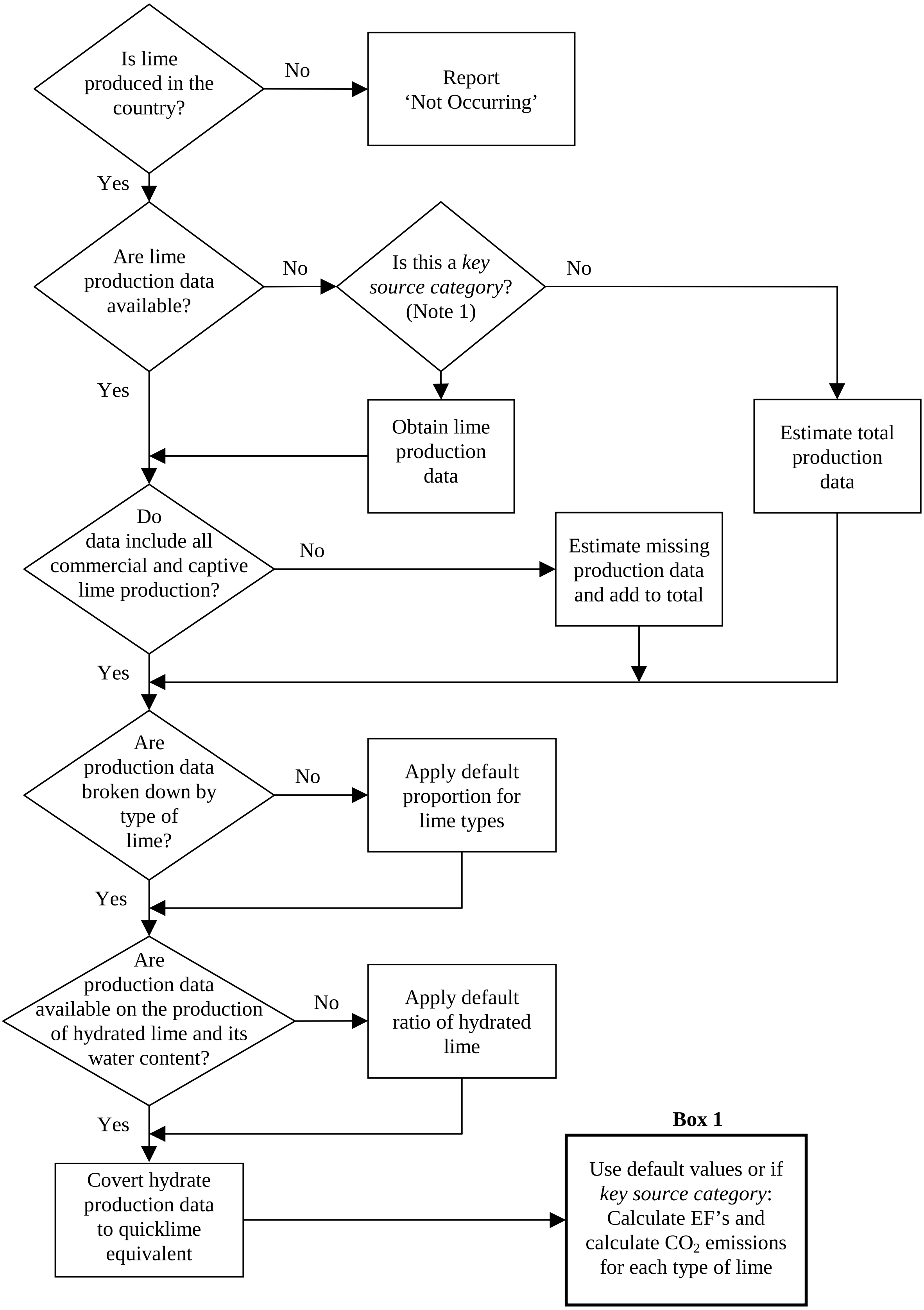
[7] Emissions from limestone use are also discussed separately in the *IPCC Guidelines*, but *good practice guidance* for this source category and some other related emission source categories are not presented in this report. *Good practice guidance* has not yet been developed because emissions from the source categories are assumed to be small and corresponding data are unavailable.

[8] Non-stoichiometric chemical compounds, such as the isomorphic crystal mixtures between Ca and Mg in its compounds as oxides and carbonates, are usually expressed by the chemical formula $CaO \cdot MgO$ and $CaCO_3 \cdot MgCO_3$, respectively.

Figure 3.2 Decision Tree for Lime Production



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Table 3.4, Basic Parameters for the Calculation of Emission Factors for Lime Production, provides data on stoichiometric ratio, the ranges of CaO and CaO·MgO contents and the resulting default emission factors, for the main lime types produced. There are three main types of lime:

- High-calcium lime (CaO + impurities);
- Dolomitic lime (CaO·MgO + impurities);
- Hydraulic lime (CaO + calcium silicates) that is a substance between lime and cement.

The main reason to distinguish these types is that the first two have different stoichiometric ratios, and the third has substantially lower CaO content. There is no exact chemical formula for each type of lime because the chemistry of the lime product is determined by the chemistry of the limestone or dolomite used to manufacture the lime.

Taking the types of lime into account will improve the emissions estimates. Consequently, when determining lime composition, *good practice* is to check the following two attributes: (1) the proportion of the three different types of lime, and (2) the proportion of hydrated lime in production.

When there are no disaggregated data for the breakdown of lime types, the default value for high-calcium/dolomitic lime is 85/15 (Miller, 1999) and the proportion of hydraulic lime should be assumed zero unless other information is available.

TABLE 3.4
BASIC PARAMETERS FOR THE CALCULATION OF EMISSION FACTORS FOR LIME PRODUCTION

Lime Type	**Stoichio-metric Ratio (1)**	**Range of CaO Content [%]**	**Range of MgO Content [%]**	**Default Value for CaO/ CaO·MgO Content (2)**	**Default Emission Factor (1) • (2)**	**Uncertainty Estimate in Emissions Estimates**
High-calcium lime[a]	0.79	93-98	0.3-2.5	0.95	0.75	±2%
Dolomitic lime [b]	0.91	55-57	38-41	0.95 or 0.85[c]	0.86 or 0.77[c]	±2%
Hydraulic lime [b]	0.79	65-92		0.75	0.59	±15%

Source:
[a] Miller (1999b) based on ASTM (1996b) and Schwarzkopf (1995).
[b] Miller (1999a) based on Boynton (1980).
[c] This value depends on technology used for lime production. The higher value is suggested for developed countries, the lower for developing ones.

CHOICE OF ACTIVITY DATA

Complete activity data include both lime production data and data on lime structure (including types of lime and proportion of hydrated lime).

Correction for the proportion of hydrated lime: Both high-calcium and dolomitic limes can be slaked and converted to hydrated lime that is $Ca(OH)_2$ or $Ca(OH)_2 \cdot Mg(OH)_2$.[9]

If *x* is the proportion of hydrated lime and *y* is the water content in it, it is *good practice* to multiply the production by a correction factor 1 – (x • y). Table 3.5, Correction of Activity Data for Hydrated Lime, below provides ranges for the amount water (y) in different types of lime. Default values are x = 0.10, y = 0.28 resulting in a correction factor of 0.97 (Miller, 1999).

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[9] The term 'slaked lime' can mean dry hydrated lime, putty or an aqueous solution. Assuming complete hydration and 100% pure quicklime, the water of hydration for high-calcium lime is 24% and for dolomitic lime is 27%. In practice, an excess of water over the theoretical amount is required for complete hydration (Miller, 1999).

TABLE 3.5
CORRECTION OF ACTIVITY DATA FOR HYDRATED LIME

Lime Type	Theoretical Content of Water in Hydrated Lime [%]	Content of Water in Commercial Hydrated Lime [%]	Default Water Content Correction Factor
High-calcium lime	24.3	26-28	0.28
Dolomitic lime	27.2	17-31	0.28
Hydraulic lime	–	–	–

Source: Miller (1999b) based on ASTM (1996) and Schwarzkopf (1995).

COMPLETENESS

Completeness of the activity data (e.g. lime production) is a crucial attribute of *good practice*. Typically, reported production accounts for only a portion of the actual production, if lime production is considered to be that product that is sold on the market. Use or production of lime as a non-marketed intermediate is not well accounted for or reported. For example, many plants that produce steel, synthetic soda ash, calcium carbide[10], magnesia and magnesium metal, as well as copper smelters and sugar mills, produce lime but may not report it to national agencies. Also, industries that regenerate lime from waste calcium carbonates (e.g. wood pulp and paper plants) are unlikely to report their lime production. Omission of these data may lead to an underestimation of lime production for a country by a factor of two or more.

DEVELOPING A CONSISTENT TIME SERIES

It is *good practice* to calculate emissions from lime production using the same method for every year in the time series. Where data are unavailable to support a more rigorous method for all years in the time series, *good practice* is to recalculate these gaps according to the guidance provided in Chapter 7, Methodological Choice and Recalculation.

UNCERTAINTY ASSESSMENT

The stoichiometric ratio is an exact number and therefore the uncertainty of the emission factor is the uncertainty of lime composition, in particular of the share of hydraulic lime that has 15% uncertainty in the emission factor (2% uncertainty in the other types). Therefore, the total uncertainty is 15% at most (see Table 3.4, Basic Parameters for the Calculation of Emission Factors for Lime Production).

The uncertainty for the activity data is likely to be much higher than for the emission factors, based on experience in gathering lime data (see completeness section above). Omission of non-marketed lime production may lead to an error of +100% or more. The correction for hydrated lime typically adds about ±5% to the former uncertainty.

3.1.2.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving. It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced.

To preserve an internally consistent emission time series, whenever national methods change, *good practice* is to recalculate the entire time series. If confidentiality is an issue for any type of production, estimates may be aggregated to the minimum extent possible to maintain confidentiality.

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[10] Some carbide producers may also regenerate lime from their calcium hydroxide by-products, which does not result in emissions of CO_2. In making calcium carbide, quicklime is mixed with coke and heated in electric furnaces. The regeneration of lime in this process is done using a waste calcium hydroxide (hydrated lime) [$CaC_2 + 2\ H_2O \rightarrow C_2H_2 + Ca(OH)_2$], not calcium carbonate [$CaCO_3$]. Thus, the calcium hydroxide is heated in the kiln to simply expel the water [$Ca(OH)_2 + \text{heat} \rightarrow CaO + H_2O$] and no CO_2 is released to the atmosphere.

3.1.2.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, Section 8.7, Source Category-specific QC Procedures (Tier 2), and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

In addition to the guidance in Chapter 8, specific procedures of relevance to this source category are outlined below.

Comparison of the emissions estimates using different approaches

If the bottom-up approach is used, then inventory agencies should compare the emissions estimates to the estimate calculated using national lime production data (top-down approach). The results of such comparisons should be recorded for internal documentation, including explanations for any discrepancies.

Activity data check

Inventory agencies should confirm the correct definitions of the different types of lime produced in the country (i.e. CaO and MgO content, high-calcium quicklime (CaO), and dolomitic quicklime (CaO·MgO). They should check the completeness of national statistics for limestone, lime and dolomite use by comparing them with the default list of industries using limestone provided in the *IPCC Guidelines*, Vol. 3, p 2.9).

3.1.3 Iron and steel industry

3.1.3.1 Methodological issues

Crude iron is produced by the reduction of iron oxide ores mostly in blast furnaces, generally using the carbon in coke or charcoal (sometimes supplemented with coal or oil) as both the fuel and reductant. In most iron furnaces, the process is aided by the use of carbonate fluxes (limestone). Additional emissions occur as the limestone or dolomite flux gives off CO_2 during reduction of pig iron in the blast furnace, but this source category is covered as emissions from limestone use (see the *IPCC Guidelines*, Vol. 3, Section 2.5, Limestone and Dolomite Use). Except for a small amount of carbon retained in the crude iron, all the carbon in the coke and in the fluxes is emitted as the product of combustion and calcination. Emissions also occur to a much lesser extent during the production of steel that is essentially the process of removal (generally by oxidation) of most of the carbon in crude iron.

Carbon plays the dual role of fuel and reductant. It is important not to double-count the carbon from the consumption of coke or other reducing agents if this is already accounted for as fuel consumption in the Energy Sector. Since the primary purpose of carbon oxidation is to reduce iron oxide ore to crude or pig iron (carbon is used as a reducing agent), the emissions are considered to be industrial processes emissions, and they should be preferably reported as such. If this is not the case, it should be explicitly mentioned in the inventory. This source category should include CO_2 emissions from the use of blast furnace gas as a fuel if emissions are reported in the Industrial Processes Sector.

CHOICE OF METHOD

The *IPCC Guidelines* outline several approaches for calculating CO_2 emissions from iron and steel production. The choice of a *good practice* method depends on national circumstances as shown in the decision tree in Figure 3.3, Decision Tree for the Iron and Steel Industry. The Tier 1 method calculates emissions from the consumption of the reducing agent (e.g. coke from coal, coal, petroleum coke), using emission factors similar to those used to estimate combustion emissions. The Tier 1 method is rather simple and slightly overestimates emissions. The Tier 2 method is similar to Tier 1 but includes a correction for the carbon stored in the metals produced. In addition, a very simple approach that is mentioned in the *IPCC Guidelines,* is to multiply iron and steel production by a production-based emission factor. However, this method is not considered to be *good practice*.

CO_2 emissions from limestone used as 'flux' in the reduction process are not included here because they are accounted for in the *IPCC Guidelines*, Vol. 3, Section 2.5, Limestone and Dolomite Use.[11]

Tier 2 Method

The Tier 2 method is based on tracking carbon through the production process. It is more accurate than Tier 1, but also more data-intensive. Estimating the emissions on the basis of plant-specific data for both Tier 1 and Tier 2 will avoid double counting or missing emissions. With the Tier 2 method, emissions from iron production and steel production are calculated separately. To achieve the highest accuracy, *good practice* is to develop emissions estimates at the plant-level because plants can differ substantially in their technology. If plant-level data are not available, *good practice* is to use nationally compiled production data for iron/steel production that are to be subtracted from the fuel combustion sector. Thus, detailed knowledge of the conventions in the national energy statistics and the inventory are necessary to avoid double counting or omission.

***Iron*:** *Good practice* is to use the following equation from the *IPCC Guidelines*:

EQUATION 3.6A

$$\text{Emissions}_{\text{pig iron}} = \text{Emission Factor}_{\text{reducing agent}} \bullet \text{Mass of Reducing Agent} + (\text{Mass of Carbon in the Ore} - \text{Mass of Carbon in the Crude Iron}) \bullet 44 / 12$$

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[11] Iron furnaces require limestone of higher purity than can be needed for clinker (cement) production. The *IPCC Guidelines* cite a USEPA reference that assumes 250 kg of lime is used for every tonne of iron. This value varies with the purity of ore and type of furnace, however.

Reducing agents can be coke, coal, charcoal and petroleum coke. In Table 3.6, CO_2 Emission Factors for Metal Production (tonne CO_2/tonne reducing agent), default emission factors from the *IPCC Guidelines* (Vol. 3, Table 2-12, CO_2 Emission Factors for Metal Production Generally (tonne CO_2/tonne reducing agent)) are presented for the most common reducing agents. In direct reduction techniques, other reducing agents such as CO, H_2 or natural gas are used. Plant-level or country-specific emission factors should be applied in these cases. According to the *IPCC Guidelines,* CO_2 emissions occurring from the limestone flux are reported as emissions from limestone and dolomite use (see the *IPCC Guidelines*, Vol. 3, Section 2.5, Limestone and Dolomite Use).

The amount of carbon in ore is almost zero and crude iron contains about 4% carbon.

***Steel*:** Emissions from steel production (e.g. using a basic oxygen furnace (BOF), open hearth furnace (OHF) or electric arc furnaces (EAF)) are based on the difference between the carbon contents of iron (3-5%) and steel (0.5-2%). In addition, for steel produced in electric arc furnaces it is *good practice* to add the carbon released from consumed electrodes to the emissions (roughly 1-1.5 kg carbon per tonne of steel):[12]

EQUATION 3.6B

$$\text{Emissions}_{\text{crude steel}} = (\text{Mass of Carbon in the Crude Iron used for Crude Steel Production} - \text{Mass of Carbon in the Crude Steel}) \bullet 44 / 12 + \text{Emission Factor}_{\text{EAF}} \bullet \text{Mass of Steel Produced in EAF}$$

The total emissions from iron and steel production are just the sum of the two Equations 3.6A and 3.6B above:

EQUATION 3.7

$$\text{Total emissions} = \text{Emissions}_{\text{pig iron}} + \text{Emissions}_{\text{crude steel}}$$

Tier 1 Method

Using the Tier 1 method, the carbon storage in pig iron and crude steel produced is not included as it is in the Tier 2 method. This simplifies the calculation in the sense that the carbon content information in the metals produced is not required. When using the Tier 1 method, it is *good practice* to calculate the emissions as follows:

EQUATION 3.8

$$\text{Emissions} = \text{Mass of Reducing Agent} \bullet \text{Emission Factor}_{\text{reducing agent}}$$

The coke and charcoal consumption in the iron and steel industry can be used to estimate the mass of reducing agents, if plant-specific information on the fuels used as reducing agent is not readily available (while subtracting the same amount from the fuel combustion sector). This step affects only the sectoral allocation of the CO_2 emissions, not the total amount. The error made in neglecting the carbon storage term of Tier 2 will be 1-5% if all pig iron produced is used for the production of crude steel and at maximum 10% if all pig iron is used for other purposes (e.g. in cast iron foundries). Thus, this method will result in a small overestimation of the source.

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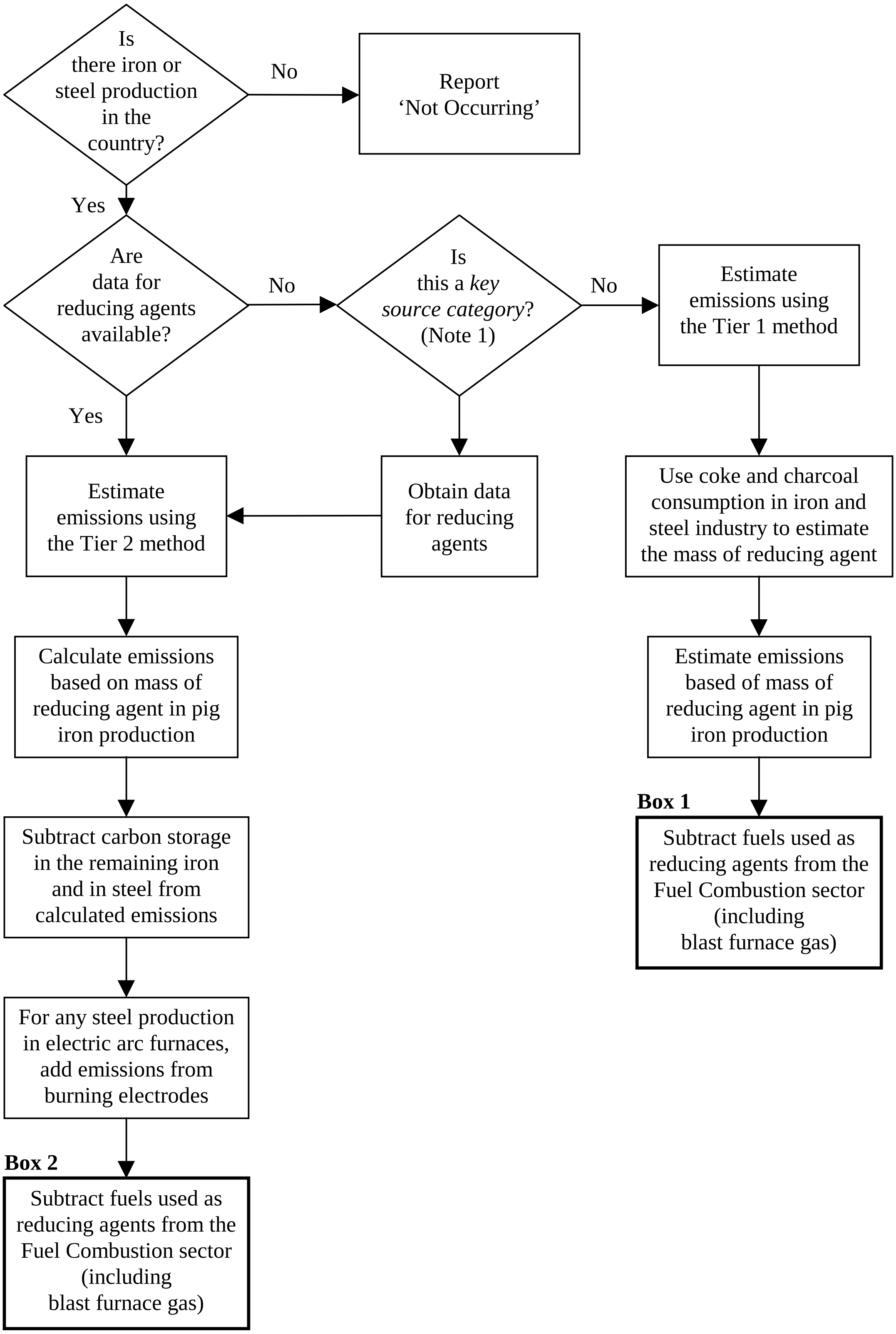
[12] Lime is added to electric arc furnaces (EAF) and its CO_2 emission should be accounted for in the lime use section (see the *IPCC Guidelines*, Vol. 3, Section 2.5). The carbon emissions factor is based on carbon loss from the electrode as an average value for the following process: In the EAF, the electrodes are made of carbon – either graphite or as Søderberg paste. Where the electrodes are kept above the steel melt (liquid), the electrical arc oxidises the carbon to CO or CO_2. The rate of gas production will vary with the electrode type and various other factors. Also, the heat causes oxidation of carbon in the melt, reducing it from around 4% for crude iron to 2% or less (usually less than 1%) in steel. Sometimes, the electrode is immersed in the melt to increase the carbon content of the steel, should too much carbon have been burned out of the melt. In this case, carbon is removed from the electrode, but may or may not result in CO_2 production. If the EAF is adjusted correctly, just enough electrode erosion is allowed to restore the steel's carbon content to the desired level. If the EAF is not efficient, excess working electrode erosion happens to excess, the electrode is retracted to above the melt, and excess carbon in the melt is burned off.

Figure 3.3 Decision Tree for the Iron and Steel Industry



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Note 2: CO_2 emissions from limestone used as 'flux' in the reduction process are not included here since they are accounted for in the *IPCC Guidelines*, Vol. 3, section 2.5, on CO_2 emissions from limestone and dolomite use.

CHOICE OF EMISSION FACTORS

If country-specific data at the plant level are not available, the default emission factors for reducing agents in the pig iron production can be taken from the *IPCC Guidelines*, Vol. 3, Table 2-12 (see Table 3.6, CO_2 Emission Factors for Metal Production (tonne CO_2/tonne reducing agent)).

TABLE 3.6
CO_2 EMISSION FACTORS FOR METAL PRODUCTION (TONNE CO_2/TONNE REDUCING AGENT)

Reducing Agent	**Emission Factor**[a]
Coal[b]	2.5
Coke from coal[b]	3.1
Petrol coke	3.6

[a] If better information on actual carbon content is not available nationally or cannot be calculated from data in the *IPCC Guidelines*, Vol. 3, Chapter 1.
[b] Derived from data in the *IPCC Guidelines*, Vol. 3, Chapter 1.

Source: *IPCC Guidelines*, Reference Manual, Table 2-12.

In direct reduction techniques, other reducing agents such as CO, H_2 or natural gas are used, each with a specific emission factor. It is *good practice* to use plant specific emission factors for steel produced in an EAF. If plant-level data are not available, a default emission factor for the electrode oxidation should be used. For the Tier 2 method, a default emission factor of 5 kg CO_2 per tonne of steel produced in EAFs should be used for the electrode consumption from the steel produced in electric arc furnaces (emission factor_{EAF}) (Tichy, 1999).

CHOICE OF ACTIVITY DATA

Tier 2 Method

Activity data should be collected at the plant-level. The most important datum is the amount of reducing agent used for iron production. If this is not a *key source category* and plant-specific data are not available, the mass of reducing agent can be estimated using the Tier 1 approach (see below). In addition, the amount of pig iron produced as well as the amounts used for crude steel production, and their carbon contents, should be collected along with data on the amount of crude steel produced in EAFs and the amount of iron in ore and its carbon content.

Tier 1 Method

The Tier 1 method requires only the amount of reducing agent used for iron production. If plant-specific data on the mass of reducing agent are not available, they can be estimated by subtracting the amount of fuel used in the iron and steel industry (ISIC 1990) for the iron ore reduction from the fuel use and reported in the Energy Sector. The amount of fuel used for the reduction can be calculated from the mass balance of the chemical formula to reduce iron ore. This rough estimation affects only the allocation of the CO_2 emissions between the Industrial Processes and the Energy Sector.

COMPLETENESS

In estimating emissions from this source category, there is a risk of double-counting or omission in either the Industrial Processes or the Energy Sector. Since the primary use of coke oxidation is to produce pig iron, the emissions are considered to be industrial processes, and it should be reported as such. If this is not the case it should be explicitly mentioned in the inventory. Inventory agencies should perform a double counting/completeness check. This will require good knowledge of the inventory in that source category.

DEVELOPING A CONSISTENT TIME SERIES

Emissions from iron and steel production should be calculated using the same method for every year in the time series. Where data are unavailable to support a more rigorous method for all years in the time series, these gaps should be recalculated according to the guidance provided in Chapter 7, Methodological Choice and Recalculation.

UNCERTAINTY ASSESSMENT

For both Tier 1 and 2 the most important type of activity data is the amount of reducing agent used for iron production. According to Chapter 2, Energy, energy data have a typical uncertainty of about 5% (about 10% for countries with less developed energy statistics). For calculating the carbon storage term Tier 2 requires additional activity data on amounts of pig iron and net crude steel production that have a typical uncertainty of a few percent. In addition, Tier 2 requires information on the carbon content of pig iron, crude steel, and of iron ore that may have an uncertainty of 5% when plant-specific data are available. Otherwise the uncertainty in the carbon content could be of the order of 25 to 50%. Finally, the uncertainty in the emission factors for the reducing agent (e.g. coke) are generally within 5% (see Section 2.1.1.6, CO_2 Emissions from Stationary Combustion, Uncertainty Assessment).

The systematic error made in emissions estimated in Tier 1 by neglecting the carbon storage term of Tier 2 will be 1-5% if all pig iron produced is used for the production of crude steel and at maximum 10% if all pig iron should be used for other purposes, i.e. in cast iron foundries. Thus, this method will result in a small overestimation of the source.

3.1.3.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving. It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced.

Tier 2 Method

Good practice is to document the emissions, all activity data (reducing agents, carbon stored, steel produced in EAFs, electrodes), in addition to corresponding emission factors and assumptions used to derive them. There should be an explanation of the linkage with the Fuel Combustion Sub-sector estimate to demonstrate that double counting or missing emissions have not occurred.

Tier 1 Method

Besides the emissions, *good practice* is to report the amount of reducing agents and their emission factors. In the corresponding table, reported emissions are only part of total emissions and the rest are reported elsewhere (Fuel Combustion Section).

In addition, inventory agencies should for both tiers, document all information needed to reproduce the estimate, as well as the QA/QC procedures.

3.1.3.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, Section 8.7, Source Category-specific QC Procedures (Tier 2), and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

In addition to the guidance in Chapter 8, specific procedures of relevance to this source category are outlined below.

Activity data check

For the Tier 2 method, inventory agencies should check with Fuel Combustion as mentioned in Section 2.1.1.4 to ensure that emissions from heating/reducing agents (coal, coke, natural gas, etc.) are not double counted or omitted.

Inventory agencies should examine any inconsistency between data from different plants to establish whether these reflect errors, different measurement techniques or result from real differences in emissions, operational conditions or technology. This is particularly relevant to the plant-specific estimates of the mass of the reducing agent.

Inventory agencies should compare aggregated plant-level estimates to industry totals for carbon and limestone consumption where such trade data are available.

3.2 N_2O EMISSIONS FROM ADIPIC ACID AND NITRIC ACID PRODUCTION

3.2.1 Methodological issues

Nitrous oxide (N_2O) is generated as an unintended by-product during the production of adipic acid and nitric acid (HNO_3), and in many industrial processes that use nitrogen oxides or nitric acids as feedstocks (e.g. the manufacture of caprolactam, glyoxal, and nuclear fuel reprocessing). Adipic acid and nitric acid are large sources of atmospheric N_2O if not abated.[13] Emissions of N_2O from these processes depend on the amount generated in the specific production process and the amount destroyed in any subsequent abatement process. Abatement of N_2O can be intentional, through installation of equipment specifically designed to destroy N_2O in adipic acid plants, or unintentional in systems designed to abate other emissions such as nitrogen oxides (NO_x). For further discussion, see Reference Manual of the *IPCC Guidelines* (Sections 2.9 and 2.10, Nitric Acid Production and Adipic Acid Production).

CHOICE OF METHOD

The choice of *good practice* methods depends on national circumstances. The decision tree in Figure 3.4, Decision Tree for N_2O Emissions from Adipic Acid and Nitric Acid Production describes *good practice* in adapting the methods in the *IPCC Guidelines* to these national circumstances. The decision tree should be applied separately to adipic and nitric acid production.

The *IPCC Guidelines* present a basic equation for estimating N_2O emissions in which production data is multiplied by an emission factor. Given the current and potential future use of N_2O abatement technologies, particularly in adipic acid plants, it is *good practice* to include an additional term in this equation as follows:

EQUATION 3.9

$$N_2O\ \text{Emissions} = \text{Specific Emission Factor} \bullet \text{Production Level} \bullet [1 - (N_2O\ \text{Destruction Factor} \bullet \text{Abatement System Utilisation Factor})]$$

The N_2O destruction factor has to be multiplied by an abatement system utility factor in order to account for any down time of the emission abatement equipment (i.e. time the equipment is not operating).

To achieve the highest accuracy, *good practice* is to apply this equation at the plant-level using N_2O generation and destruction factors developed from plant-specific measurement data. In this case, the national total is equal to the sum of plant totals. Where plant-level information is not available, *good practice* provides default N_2O generation factors and destruction factors as shown in Tables 3.7, Default Factors for Adipic Acid Production, and 3.8, Default Factors for Nitric Acid Production, based on the plant types and abatement technologies implemented.

Given the relatively small number of adipic acid plants (about 23 globally, Choe *et al.*, 1993), obtaining plant-specific information requires few additional resources. However, there are more nitric acid plants (estimates range from 255 to 600 plants according to Choe *et al.*, 1993,, Bockman and Granli, 1994) with a much greater variation in the N_2O generation factors among plant types. Thus, default factors may be needed more often for nitric acid N_2O emissions estimates. Where default values are used to estimate emissions from nitric acid production, it is *good practice* to categorise plants according to type and to use an appropriate N_2O generation factor used to the extent possible.

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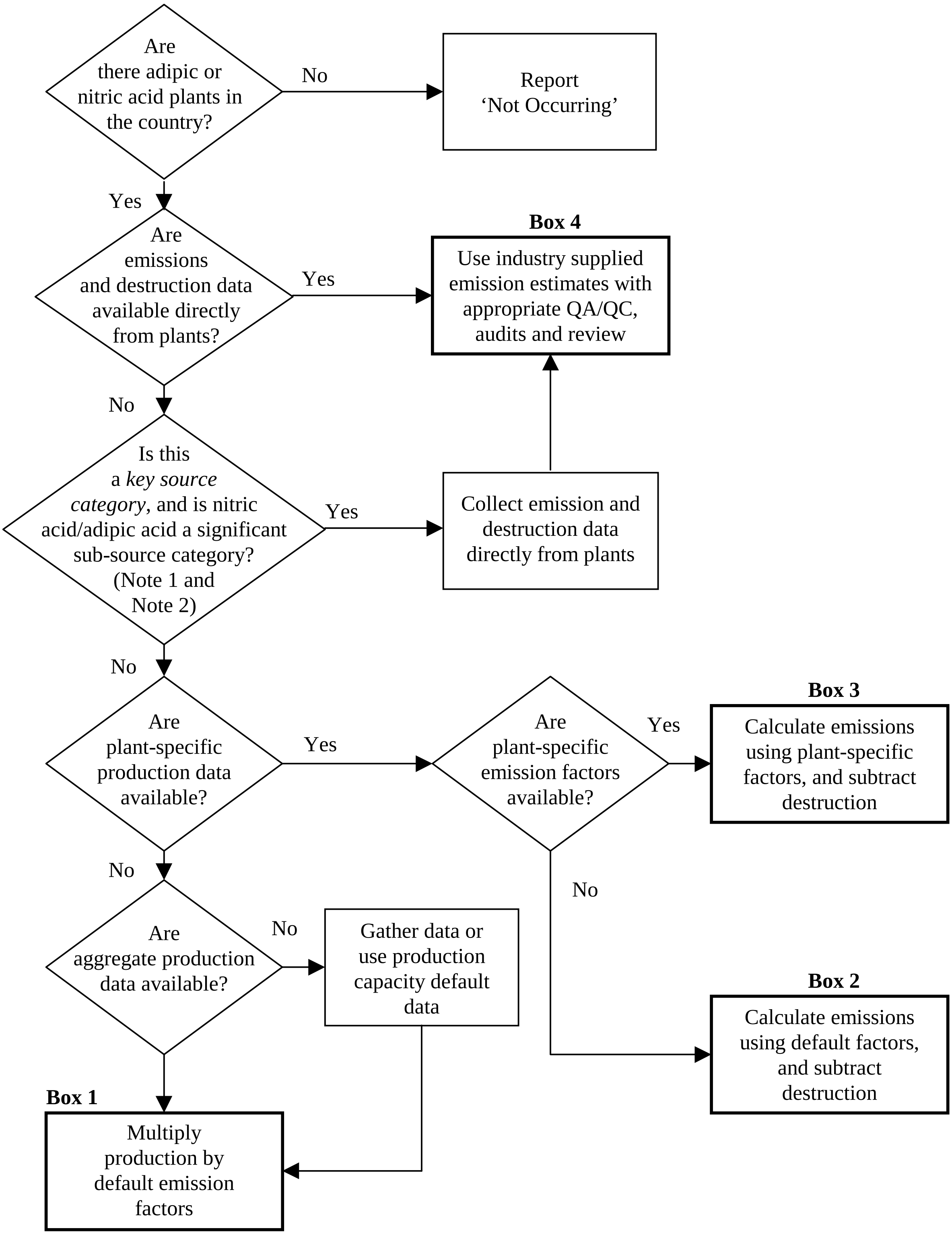
[13] The chemical and other industries included in this section are generally unrelated except for the fact that nitric acid is used in the manufacture of adipic acid. The manufacturing technologies and the applicable technologies for abating N_2O are very different for each industry.

Figure 3.4 Decision Tree for N_2O Emissions from Adipic Acid and Nitric Acid Production



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Note 2: As a rule of thumb, a sub-source category would be significant if it accounts for 25-30% of emissions from the source category.

CHOICE OF EMISSION FACTORS

Plant measurements provide the most rigorous data for calculating net emissions (i.e. N_2O generation and destruction factors). Monitoring N_2O emissions from both adipic acid and nitric acid production is practical because these are point sources and there are a finite number of production plants. Given currently available technology, instrumentation for sampling and monitoring emission rates do not limit precision or accuracy of the overall measurement. Usually sampling frequency and timing is sufficient to avoid systematic errors and to achieve the desired level of accuracy. As a general rule, it is *good practice* to conduct sampling and analysis whenever a plant makes any significant process changes that would affect the generation rate of N_2O, and sufficiently often otherwise to ensure that operating conditions are constant. In addition, plant operators should be consulted annually to determine the specific destruction technologies employed and confirm their use, since technologies may change over time. Precise measurement of the emissions rate and abatement efficiencies requires measurement of both the exit stream and the uncontrolled stream. Where measurement data are available only on the exit stream, *good practice* is to base emissions on these data. In this case, any available estimates of abatement efficiency should be provided only for information purposes and not used to calculate emissions.

If plant-level factors are not available, it is *good practice* to use default factors. These default values often represent midpoint or mean values of data sets (as determined by expert analysis). The extent to which they represent a specific plant’s emission rate is unknown. Default factors should be used only in cases where plant-specific measurements are not available.

Table 3.7, Default Factors for Adipic Acid Production, presents default emission factors for adipic acid production, and default N_2O destruction factors for commonly used abatement technologies, and associated uncertainties. This table supplements the *IPCC Guidelines* default values by providing information about N_2O abatement technologies. Failure to determine if abatement technologies are being used can result in overestimation of emissions.

Table 3.8, Default Factors for Nitric Acid Production, supplements the emission factors for nitric acid production provided in the *IPCC Guidelines* (Vol. 3, Section 2.9, Table 2-7, Emission Factors for N_2O from Nitric Acid Production). It also includes additional emission and destruction factors for NO_x abatement technologies, and associated uncertainties. The generation factors listed in Table 3.8 for plants using non-selective catalytic reduction (NSCR) already incorporate the effect of abatement measures. The N_2O destruction factor for NSCR in Table 3.8 is provided for information purposes only and should not be applied to an emissions estimate using the NSCR default generation factor because this would double-count the destruction.

TABLE 3.7
DEFAULT FACTORS FOR ADIPIC ACID PRODUCTION

Production Process	**N_2O Generation Factor**[a,d]	**Uncertainty Estimate**
Nitric Acid Oxidation	300 kg/tonne adipic acid	± 10% (based on expert judgement). The range of 300 kg ± 10% encompasses the variability from pure ketone to pure alcohol feedstocks, with most manufacturers somewhere in the middle.[a]
Abatement Technology	**N_2O Destruction Factor**[b]	**Uncertainty Estimates (distinct from destruction factor ranges)**
Catalytic Destruction	90-95%	± 5% (based on expert judgement). Manufacturers known to employ this technology include: BASF (Scott, 1998), and DuPont (Reimer, 1999b).
Thermal Destruction	98-99%	± 5% (based on expert judgement). Manufacturers known to employ this technology include: Asahi, DuPont, Bayer, and Solutia (Scott, 1998).
Recycle to feedstock for Phenol	98-99%	± 5% (based on expert judgement). Manufacturers known to employ this technology include: Alsachemie (Scott, 1998).
Recycle to feedstock for Adipic Acid	90-98%	± 5% (based on expert judgement). Solutia will be implementing this technology around 2002 (Scott, 1998).
Abatement System	**Utilisation Factor**[e]	
Catalytic Destruction	80-98%	See Note c
Thermal Destruction	95-99%	See Note c
Recycle to Nitric Acid	90-98%	See Note c
Recycle to Adipic Acid	80-98%	See Note c

[a] With regard to the Japan Environment Agency value (264 kg N_2O/tonne adipic acid) provided in the *IPCC Guidelines*, it is believed that this manufacturer uses oxidation of pure cyclohexanol (alcohol), instead of a ketone-alcohol mixture (Reimer, 1999). This is the only plant known to use this method.

[b] The destruction factor (that represents the technology abatement efficiency) should be multiplied by an abatement system utility factor. Note that this range is not an uncertainty estimate.

[c] Note that these default values are based on expert judgement and not industry-supplied data or plant-specific measurements. In the first 1-5 years of the abatement technology implementation, the utilisation factor tends to be at the lower end of the range. Lower utility of the equipment typically results because of the need to learn how to operate the abatement system and because more maintenance problems occur during the initial phase. After 1-5 years, the operating experience improves and the utilisation factor would tend to be at the high end of the range.

Source:
[d] Thiemans and Trogler, 1991.
[e] Reimer, 1999b.

TABLE 3.8
DEFAULT FACTORS FOR NITRIC ACID PRODUCTION

Production Process	**N_2O Generation Factor** **(kg N_2O/tonne nitric acid)**	**Special Considerations**
Canada	8.5	Based on an average emissions rate for plants of European design (Collis, 1999)
- plants without NSCR[a]		
- plants using NSCR	<2	The N_2O generation factor accounts for N_2O destruction by NSCR. Uncertainty = ± 10% (based on expert judgement – Collis, 1999).
USA	9.5	An estimated 80% of nitric acid (HNO_3) plants do not use NSCR systems (Choe *et al.*, 1993).
- plants without NSCR		
- plants using NSCR	2	The N_2O generation factor accounts for N_2O destruction by NSCR. Industry indicates a range of 1.12 to 2.5 kg N_2O/tonne HNO_3, field experts have indicated that the lower end of the range is more accurate (Choe *et al.*, 1993,, Collis, 1999). A factor of 2 was selected as a conservative default. An estimated 20% of HNO_3 plants use NSCR systems (Choe *et al.*, 1993). Uncertainty = ± 10% (based on expert judgement).
Norway	<2	Norsk Hydro developed a state-of-the-art reactor design in which emissions of N_2O are reduced in a process-integrated manner (Norsk Hydro, 1996). There is only one installation operational of this type (Oonk, 1999).
- process-integrated N_2O destruction		
- atmospheric pressure plant (low pressure)	4-5	(Norsk Hydro, 1996)
- medium pressure plant	6-7.5	(Norsk Hydro, 1996)
Japan	2.2-5.7	(Japan Environment Agency, 1995)
Other Countries	8-10	
- European designed, dual pressure, double absorption plants		
- Older (pre - 1975), plants without NSCR	10-19	Emission factors up to 19 kg N_2O/tonne nitric acid have been reported for plants not equipped with NSCR technology (Choe *et al.*, 1993, EFMA, 1995). Such a high emissions rate would most likely apply to outdated plants (Choe 1993, Cook (1999).
NO_x Abatement Technology	**N_2O Destruction Factor (%)**	**Notes**
Non-Selective Catalytic Reduction (NSCR)	80-90	Uncertainty = ± 10% (based on expert judgement). NSCR is a typical tail gas treatment in the USA and Canada with less application in other parts of the world.
Selective Catalytic Reduction (SCR)	0	SCR with ammonia does not reduce N_2O.
Extended Absorption	0	

[a] Non-Selective Catalytic Reduction (NSCR).

CHOICE OF ACTIVITY DATA

It is *good practice* to gather activity (production) data at a level of detail consistent with that of the generation and destruction data. Where plant-level emission factors are used, *good practice* is to collect plant-level production data. Typical plant-level production data is accurate to ±2% due to the economic value of having accurate information . If plant-level data are not available, nationally compiled production data may be used. However, for the nitric acid source category, these statistics may miss an average of one-half of a national total (see details in Completeness Section).

If neither plant-level nor national-level activity data are available, information on production capacity can be used. It is *good practice* to multiply the total national production capacity by a capacity utilisation factor of 80% ± 20% (i.e. range of 60-100%).

COMPLETENESS

Complete coverage for the adipic acid source category is straightforward, but nationally compiled nitric acid production statistics may miss an average of one-half of the total. Studies that compare global statistics compiled from national data on nitric acid production with industry estimates of global production suggest that the national statistics account for only 50 to 70% of the total (Bouwman *et al.*, 1995, Olivier, 1999). This is probably due to nitric acid production that is integrated as part of larger production processes, where the nitric acid never enters into commerce and is not counted in the national statistics. For example, in the manufacture of caprolactam, nitrogen oxides produced via ammonia oxidation are used directly in the process without prior conversion to nitric acid. Accounting for these sources by methods such as identifying them through national registries of NO_x emissions, another unintended by-product of nitric acid production, will improve completeness.

DEVELOPING A CONSISTENT TIME SERIES

N_2O emissions should be recalculated for all years whenever emission calculation methods are changed (e.g. if the inventory agency changes from the use of default values to actual values determined at the plant level). If plant-specific data are not available for all years in the time series, it will be necessary to consider how current plant measurements can be used to recalculate emissions for previous years. It may be possible to apply current plant-specific emission factors to production data from previous years, provided that plant operations have not changed substantially. Such a recalculation is required to ensure that any changes in emissions trends are real and not an artefact of changes in procedure. It is *good practice* to recalculate the time series according to the guidance provided in Chapter 7, Methodological Choice and Recalculation.

UNCERTAINTY ASSESSMENT

Uncertainties for the default values are estimates based on expert judgement. In general, adipic acid default emission factors are more certain than nitric acid default emission factors because they are derived from the stoichiometry of an intended chemical reaction (nitric acid oxidation) and N_2O-specific abatement systems. The uncertainty in the emission factor for adipic acid represents a variability in N_2O generation due to differences in the composition of the cyclohexanone and cyclohexanol feedstock (i.e. ketone and alcohol) that are used by different manufacturers. Higher ketone content results in increased N_2O generation, whereas higher alcohol content results in less N_2O generation (Reimer, 1999a). An individual plant should be able to determine the production of N_2O (based on HNO_3 consumption) within 1%. In contrast, the default values for nitric acid production are much more uncertain. First, N_2O may be generated in the gauze reactor section of nitric acid production as an unintended by-product reaction (Cook, 1999). Second, the exhaust gas may or may not be treated for NO_x control, and the NO_x abatement system may or may not reduce (or may even increase) the N_2O concentration of the treated gas. [14]

Although there is greater uncertainty associated with nitric acid values than those for adipic acid, potential N_2O emissions per metric ton produced are far greater for adipic acid production. Thus, the uncertainty associated with adipic acid production may be more significant when converted into N_2O emissions. A properly maintained and calibrated monitoring system can determine emissions using Equation 3.9 above to within ±5% at the 95% confidence level.

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[14] In some cases, processes designed to reduce NO_x emissions may result in additional N_2O generation. Increased N_2O concentrations due to NO_x abatement technology have been measured at various power plants that employ non-catalytic reduction for NO_x (Cook, 1999). From at least one nitric acid plant, it is known that NO_x control resulted in increased N_2O emissions (Burtscher, 1999).

3.2.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving.

Some examples of specific documentation and reporting relevant to this source category are provided below:

- Description of the method used;
- Number of adipic acid and nitric acid plants, respectively;
- Emission factors;
- Production data;
- Production capacity;
- Number of plants using abatement technology;
- Type of abatement technology, destruction efficiency, and utilisation;
- Any other assumptions.

BOX 3.1
OTHER POTENTIAL INDUSTRIAL N_2O SOURCES

The Reference Manual of the *IPCC Guidelines* identifies several other potential N_2O source categories of unknown magnitude, but which are believed to be small. Potential N_2O non-combustion industrial source categories include: caprolactam production, urea production, petrochemical production, propellant and foaming agents, fumes from explosives, dodecanedioic acid production (DDDA or 3DA), and fume sweep from adipic acid and nitric acid tanks. Inventory agencies that quantify such source categories should report the data in their inventory and provide documentation of their method. This information could provide a basis for subsequent revisions of the *IPCC Guidelines.*

Plant operators should supply this information to the inventory agency for compilation, and also archive the information at the site. Plant operators should also log and archive the measurement frequencies and instrumental calibration records where actual plant measurements are made.

Where there are only one or two producers in a country, as could often be the case for adipic acid production, activity data may be considered confidential. In this case, operators and the inventory agency should determine the level of aggregation at which information can be reported while still protecting confidentiality. Detailed information including instrumentation records should still be archived at the plant level.

It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced.

3.2.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, Section 8.7, Source Category-specific QC Procedures (Tier 2), and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

In addition to the guidance in Chapter 8, specific procedures of relevance to this source category are outlined below.

Comparison of emissions estimates using different approaches

If emissions are calculated using data from individual adipic acid and nitric acid plants (bottom-up approach), inventory agencies should compare the estimate to emissions calculated using national production data (top-down approach). They should record the results and investigate any unexplained discrepancies.

Since industrial N_2O source categories are relatively small compared to other anthropogenic and natural sources, it is not feasible to compare emissions with measured trends in atmospheric N_2O concentrations.

Plant-level data

Inventory agencies should archive sufficient information to allow an independent review of the time series of emissions beginning in the base year, and to explain trends in emissions when making historical comparisons. This is particularly important in cases where recalculations are necessary, for example, when an inventory agency changes from using default values to actual values determined at the plant level.

Revision of direct emission measurements

If plant-level N_2O measurements are available, inventory agencies should confirm that internationally recognised, standard methods were used. If the measurement practices fail this criterion, then they should evaluate the use of these emissions data. In addition, they should reconsider the uncertainty estimates in light of the QA/QC results.

Inventory agencies should compare plant-based factors to the IPCC defaults to ensure that the plant-specific factors are reasonable. They should explain and document any differences between plant-specific factors and default factors, particularly any differences in plant characteristics that might lead to these differences.

3.3 PFC EMISSIONS FROM ALUMINIUM PRODUCTION

3.3.1 Methodological issues

Two PFCs, tetrafluoromethane (CF_4), and hexafluoroethane (C_2F_6) are known to be emitted from the process of primary aluminium smelting. These PFCs are formed during the phenomenon known as the anode effect (AE), when the aluminium oxide concentration in the reduction cell electrolyte is low.

CHOICE OF METHOD

The choice of a *good practice* method will depend on national circumstances. The decision tree in Figure 3.5, Decision Tree for PFC Emissions from Aluminium Production describes *good practice* in adapting the methods in the *IPCC Guidelines* to these country-specific circumstances. The decision tree should be applied separately for CF_4 and C_2F_6 emissions estimation.

The *IPCC Guidelines* describe three general methods for estimating PFC emissions from aluminium production (Vol.3, Section 2.13.6, PFCs from Aluminium Production). These three methods correspond to tiers, but are not identified as such. To be consistent with other sections of the *IPCC Guidelines* and the *good practice guidance*, the methods presented in the *IPCC Guidelines* are referred to as tiers in this section.

The most accurate method is either to monitor smelter emissions continuously (Tier 3a) or to develop a smelter-specific long term relationship between measured emissions and operating parameters and to apply this relationship using activity data (Tier 3b). The Tier 3b method requires comprehensive measurements to develop the smelter-specific relationship and on-going collection of operating parameter data (e.g. frequency and duration of anode effects and the Anode Effect Overvoltage[15]) and production data. Where a smelter-specific relationship has not been developed but information on operating parameters and production is available, default technology-specific slope and overvoltage coefficients may be used (Tier 2). Where the only information available is the annual quantity of aluminium produced, default emission factors by technology type may be used (Tier 1). The level of uncertainty in the Tier 1 method will be much greater than for estimations produced using Tier 3 or Tier 2 methods.

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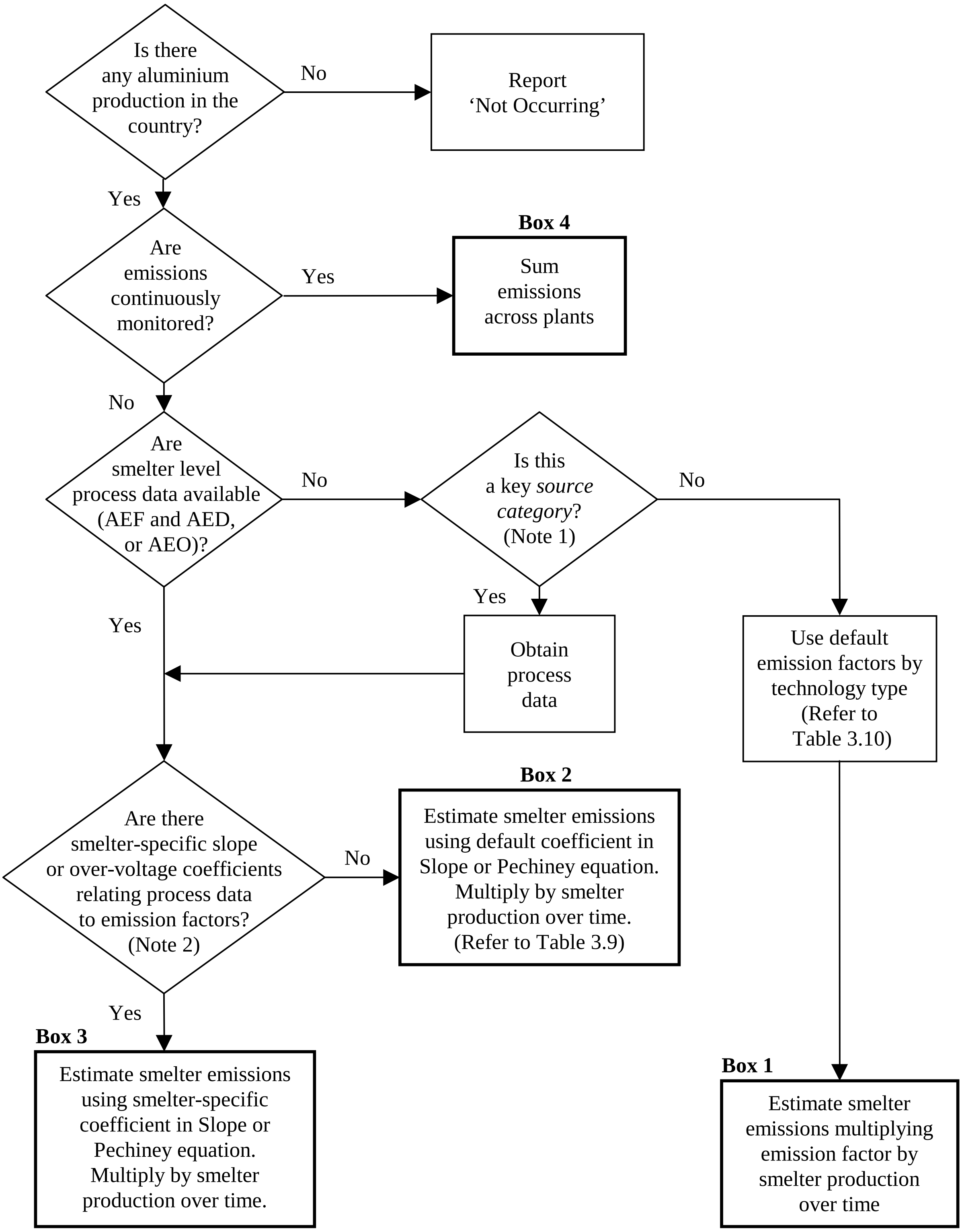
[15] The Anode Effect Overvoltage indicates the fluctuation in voltage occurring during the anode effect.

Figure 3.5 Decision Tree for PFC Emissions from Aluminium Production



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Note 2: In cases where a smelter has more than one distinct cell technology, a smelter must measure/use specific emission coefficients for each technology.

Tier 3a Method – Continuous emission monitoring

Continuous monitoring of emissions is possible and is the most accurate means of determining emissions. Given likely cost and other resource considerations, however, it is not regarded as necessary for *good practice*. For details on direct measurement techniques, see Box 3.2, Direct Measurement Techniques, below.

BOX 3.2
DIRECT MEASUREMENT TECHNIQUES

Sampling and measurement must be performed to a *good practice* standard to ensure the accuracy of the data, which means that:

- Measurements of PFCs at smelters should account for both emissions captured by the reduction cell hooding and extracted by the fume exhaust duct, and also fugitive emissions released into the potroom[16] atmosphere. Ideally, these data can be obtained by direct measurement of PFCs in duct and fugitive emissions. Otherwise, direct measurement of PFCs in duct emissions can be conducted along with careful measurement of the cell hooding capture efficiency, allowing fugitive emissions to be calculated.

- The analytical technology used should be capable of measuring both CF_4 and C_2F_6 gases simultaneously. Several suitable analytical technologies are available. The technology chosen must have a suitable dynamic range for the measurement of expected concentrations of duct emissions and fugitive emissions. The sensitivity of the detection should be capable of reliable measurement at the lowest levels expected in electrolysis cell exhaust ducts and for fugitive emissions where fugitive emissions account for 5% or more of total PFC emissions. The dynamic range of the measurement device should be capable of reliable measurement to the highest concentration to be measured. For duct emissions, this means a concentration measurement range of 0 to 1000 ppmv (parts per million by volume). Measurements should be normalised for temperature and pressure and these measurement conditions must be reported and recorded with the concentration measurements that will be used when calculating mass emissions.

- Duct volumetric gas flow measurements should be performed according to nationally or internationally recognised standards. Gas flow measurements should be performed during the course of the concentration measurement program at sufficient intervals to ensure accurate representation of the volumetric gas flow. Measurements should be normalised for temperature and pressure and these measurement conditions must be reported and recorded with the flow measurements that will be used when calculating mass emissions.

- Calibration of analytical instruments should be performed at regular intervals during the measurement campaign. The required schedule for calibrations will vary according to the type and known stability of the analytical instrumentation used but must be sufficient to minimise the effect of instrument calibration drift. The results of all calibrations should be reported and recorded with the concentration measurement. Measurements affected by drift should be omitted from emission estimations. Calibration gases should be traceable to recognised national or international standards. The calibration method should be thoroughly documented and recorded with the emission measurements. Chapter 8, Quality Assurance and Quality Control, provides general advice on sampling representativeness.

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[16] The potroom is the standard industry term for the large room in which the reduction cells or 'pots' are housed. The smelting cells have hooding which, depending on the smelter design, age etc., will have varying fume collection efficiency. The collected fume is transported via ducts to a fume scrubbing facility where other pollutants are removed. Fume that escapes from the hooding may either be collected in a fume manifold and also transported to the fume scrubbing facility or exhausted to atmosphere through the potroom roof. Since the potrooms may be up to a kilometre long and 20 metres or more in width, accurate measurements of fugitive emissions may not be feasible. Therefore, measurements of PFCs in collected fume and fugitive fume are required or else measurements of collected fume along with a comprehensive understanding of the fume collection efficiency is required to ensure that PFCs captured by the scrubbing system along with fugitive emissions are included in estimations.

Tier 3b Method – Smelter-specific relationship between emissions and operating parameters based on field measurements

This method uses periodic measurements to establish a smelter-specific relationship between operating parameters (i.e. frequency and duration of anode effects or Anode Effect Overvoltage) and emissions of CF_4 and C_2F_6. Once established, the relationship can be used along with process data collected on an on-going basis, to estimate emissions factors over time. These emission factors are multiplied by smelter-specific production (tonnes) to estimate smelter emissions. Emissions estimates will be aggregated across smelters to estimate national emissions.

The following estimation relationships can be used:

Slope Method: This method uses a linear least squares relationship between anode effect (AE) minutes per cellday[17] and emissions, expressed as an emission factor (EF):

EQUATION 3.10

$$\text{EF (kg } CF_4 \text{ or } C_2F_6 \text{ per tonne of Al)} = \text{Slope} \bullet \text{AE min / cellday}$$

To develop an accurate estimate of the slope, simultaneous measurements of emissions and collection of anode effect data over an appropriate period of time are required. The Slope Method is a variant of the **Tabereaux approach** described in the *IPCC Guidelines*:

BOX 3.3

TABEREAUX APPROACH

$$\text{Slope} = 1.698 \bullet (p / CE) \quad \text{and} \quad \text{AE min / cellday} = \text{AEF} \bullet \text{AED}$$

Where:

p = Average fraction of CF_4 in the cell gas during anode effects for the CF_4 slope or the average fraction of C_2F_6 in the cell gas during anode effects for the C_2F_6 slope

CE = Current Efficiency for the aluminium production process

AEF = Number of anode effects per cellday

AED = Anode effect duration in minutes

Pechiney Overvoltage Method: This method uses the Anode Effect Overvoltage as the relevant process parameter. The Anode Effect Overvoltage is the extra cell voltage, above 8V, caused by anode effects, when averaged over a 24-hour period (mV/day). The correlation formula was derived from measurements of PFC generation at smelters with Pechiney technology, expressed as an emission factor (EF):

EQUATION 3.11

$$\text{EF (kg } CF_4 \text{ or } C_2F_6 \text{ per tonne of Al)} = \text{Over-Voltage Coefficient} \bullet \text{AEO / CE}$$

Where:

AEO = Anode effect over-voltage in mV/cellday

CE = Aluminium production process current efficiency expressed as a fraction

Tier 2 Method – smelter-specific relationship between emissions & operating parameters based on default technology-based slope and over-voltage coefficients

If measurement data are not available to determine smelter-specific Slope or Overvoltage coefficients, default coefficients may be used together with smelter-specific operating parameters. *Good practice* default coefficients

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[17] The 'cellday' term really means 'the number of cells operating multiplied by the number of days of operation'. At a smelter this would more usually be calculated (for a certain period of time, e.g. a month or a year) using 'the average number of cells operating across the smelter over a certain period of days multiplied by the number of days in the period'.

are listed in Table 3.9, Default Coefficients for the Calculation of PFC Emissions from Aluminium Production (Tier 2 Methods).

Tier 1 Method – Production-based emission factors

The simplest estimation method is to multiply default emission factors by aluminium production. When the only smelter-specific activity data available are metal production statistics, it is *good practice* to use default emission factors (see Choice of Emission Factors).

Default slope coefficients (Tier 2 method) and emission factors (Tier 1 method) were developed using available data from International Primary Aluminum Institute (IPAI) surveys and other field measurement data (Bouzat *et al.*, 1996, Leber *et al.*, 1998, Marks, 1998, Roberts *et al.*, 1994a and 1994b, Kimmerle *et al.*, 1998, Marks *et al.*, 2000). The limited information available for some data required expert judgement regarding the suitability of some measurement sets. As an example, the Tier 1 Method Horizontal Stud Søderberg (HSS) default emission factors were calculated using 1991 data, rather than 1990 data.

When possible, the consistency of available measurement data surveyed over different time periods and at different smelters should be used to confirm a significant degree of confidence about the magnitude and trend of the emission factors and coefficients.

CHOICE OF EMISSION FACTORS

Tier 3b Method

For this method, it is *good practice* to determine the coefficients of the models by using *smelter-specific measurements.* The smelter-specific coefficients should be based on comprehensive measurements of CF_4 and C_2F_6 emissions with simultaneous collection of process data. This means that emission factors should reflect the specific conditions of a plant and the technologies involved. Emission factors are to be measured over a period of time that reflects the variability of the process and accounts for both emissions captured by the fume collection system and fugitive emissions (if this sub-source category is significant, compared with emissions captured by the fume control system). Box 3.2, Direct Measurement Techniques, gives guidance on some aspects of direct measurement techniques. It is *good practice* to follow these approaches in implementing a sampling and measurement program.[18]

Tier 2 Method

If smelter-specific measurements are unavailable, default coefficients may be used. Default coefficients are provided by technology type in Table 3.9, Default Coefficients for the Calculation of PFC Emissions from Aluminium Production (Tier 2 Methods).[19] The default coefficients must be applied by technology type within each smelter. If more than one technology type is being used at a smelter, the appropriate default coefficients must be applied separately for each technology segment.

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[18] Other methods may incorporate an explicit factor representing a contribution from newly started cells. The smelter-specific slope coefficients developed under Tier 3b will incorporate these emissions.

[19] Current measurement programs are improving the quantity and quality of available data. These data should be available by early 2000, and may supersede the values provided in Table 3.9.

TABLE 3.9
DEFAULT COEFFICIENTS FOR THE CALCULATION OF PFC EMISSIONS FROM ALUMINIUM PRODUCTION (TIER 2 METHODS)

Technology[a]	**Slope**[b,d] **(kg** $_{PFC}$**/t**$_{Al}$**/AE-Minutes/cellday)**				**Overvoltage coefficient**[b] **(kg** $_{PFC}$**/t**$_{Al}$ **/mV/day)**	
	CF_4	**Uncertainty**	**C_2F_6**	**Uncertainty**	**CF_4**	**C_2F_6**
CWPB	0.14	±0.009	0.018	±0.004	1.9	NA
SWPB	0.29	±0.02	0.029 [c]	±0.01	1.9	NA
VSS	0.068 [g]	±0.02	0.003 [g]	±0.001	See note e	–
HSS	0.18 [f]		0.018		–	–

[a] Centre Worked Prebaked (CWPB), Side Worked Prebaked (SWPB), Vertical Stud Søderberg (VSS), Horizontal Stud Søderberg (HSS).
[b] Source: IPAI, EPA field measurements, and other company measurement data.
[c] There is inadequate data for establishing a slope coefficient for C_2F_6 emissions from SWPB cells based on measurement data; therefore a default of one-tenth of the CF_4 coefficient is *good practice*, consistent with the *IPCC Guidelines*.
[d] Embedded in each Slope coefficient is an assumed emissions collection efficiency as follows: CWPB 95%, SWPB 90%, VSS 85%, HSS 90%. These collection efficiencies have been assumed based on expert opinion. While collection efficiency for HSS cells may vary, the company measurement data used for calculation of these coefficients are consistent with a collection efficiency of at least 90%.
[e] Overvoltage coefficients are not relevant to VSS and HSS technologies.
[f] The HSS Slope coefficients are based on 1991 IPAI survey data.
[g] Further work on emission measurement and uncertainty analysis should be pursued for VSS. These default coefficients are based on a small number of data, and it is expected that the uncertainty might be higher than for other coefficients (Bjerke, 1999a, and Bjerke *et al*., 1999b).
NA = not available.

Tier 1 Method

The simplest method is to multiply default emission factors by aluminium production. Default emission factors by technology-type are available in the *IPCC Guidelines*. It is *good practice* to base these factors on recently updated measurements, and revised default emission factors and associated uncertainty ranges are presented in Table 3.10, Default Emission Factors and Uncertainty Ranges for the Calculation of PFC Emissions from Aluminium Production (by Technology Type), below. As the Tier 1 method is the most uncertain of the three approaches, it is *good practice* to use default emission factors as a method of last resort, when only metal production statistics are available.

TABLE 3.10
DEFAULT EMISSION FACTORS AND UNCERTAINTY RANGES FOR THE CALCULATION OF PFC EMISSIONS FROM ALUMINIUM PRODUCTION (BY TECHNOLOGY TYPE)

Technology	**CF_4**		**C_2F_6**	
	kg/tonne Al[e]	**Uncertainty Range**[a]	**kg/tonne Al**[e]	**Uncertainty Range**[a]
CWPB	0.31	0.0003-1.3	0.04	0.00004-0.2
SWPB	1.7	0.8-3.8	0.17 [b]	0.08-0.4
VSS	0.61 [c]	0.4-1.1	0.061 [c]	0.04-0.1
HSS	0.6 [d]	0.0006-1.4	0.06 [d]	0.00006-0.13

[a] Uncertainty was estimated by the IPCC Washington expert meeting group to a 95% confidence interval on the basis of the variance of anode effect minute data from IPAI Survey Data for 1990 (or 1991 for HSS) for each technology type.
[b] There are inadequate data for establishing an emission factor for C_2F_6 emissions from SWPB cells based on measurement data; therefore a default of one-tenth of the CF_4 coefficient is *good practice*, consistent with the *IPCC Guidelines*.
[c] The VSS default emission factors are based on IPAI, EPA field measurements, and other 1990 company measurement data. These default factors are based on a small number of data, and it is expected that the uncertainty might be higher than for other factors (Bjerke, 1999a, and Bjerke *et al*., 1999b).
[d] The HSS default emission factors are based on 1991 IPAI survey data.
[e] Source: IPAI, EPA field measurements, and other 1990 company measurement data, except for HSS that is based on 1991 data (Bjerke, 1999a, and Bjerke *et al*., 1999b).

It is *good practice* to apply the default emission factors that are based on 1990 (or 1991 for HSS) median anode effect frequency and duration data, for all years for which there are no process (anode effect) data unless it can be demonstrated otherwise.

CHOICE OF ACTIVITY DATA

It is *good practice* to record the information requested for Tier 3b and Tier 2 methods concerning frequency and duration of anode effects and Anode Effect Overvoltage and production data at the plant level. Individual companies or industry groups should be consulted to ensure that the data are available and in a useable format for inventory estimation. For the Tier 1 method, activity data consist of production statistics that should be available from companies at the plant level. Uncertainty in production data (tonnes of aluminium) is likely to be low in most countries. Given the expected universal availability of production data, production capacity data should only be used as a check on production statistics.

COMPLETENESS

In principle, production statistics should be available for all smelters. It is *good practice* to aggregate emissions estimates from each smelter to estimate total national emissions. All members of the IPAI, who represent 60% of 1999 world capacity, report production data. If smelter-level production data are unavailable, smelter capacity data may be used along with aggregate national production to estimate smelter production. All inventory agencies should be able to implement at a minimum level the Tier 1 method and ensure completeness of reporting. There is no reason to report the terms NA (not available) and NE (not estimated) for this source category. When emissions are being measured by continuous monitoring or for the purposes of calculating emission coefficients or emission factors, complete coverage of emissions at the smelter level for this source category requires estimation of emissions of CF_4 and C_2F_6 from the exhaust duct and potroom roof or a good understanding of the collection efficiency.

DEVELOPING A CONSISTENT TIME SERIES

If all the necessary historical data (e.g. production statistics, AED and AEF or AEO) are available, emissions over the entire time period can be estimated using the appropriate *good practice* method.

Where some historical data are missing, it is *good practice* to use available plant-specific measurements to establish an acceptable relationship between emissions and activity data in the base year. Implementing any relationship retroactively requires that records of process data be available. Most smelters should have records of process data, with perhaps some regional exceptions. In addition to having historical data, each smelter must be able to demonstrate that the relationship to be retroactively implemented is applicable to its historical operating conditions (i.e. there have been no significant technological or operational changes).[20] To ensure consistency over time, if the estimation method for a smelter changes it is *good practice* to recalculate emissions estimates using both the past and current methodologies to ensure that any trends in emissions are real and not caused by the change in estimation methodologies. These recalculations should be carried out according to the guidance provided in Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques, and all assumptions should be documented clearly.

UNCERTAINTY ASSESSMENT

It is possible to apply classical statistical quantitative approaches to estimate uncertainty ranges for the Tier 1, Tier 2 and Tier 3 methods. Tables 3.9, Default Coefficients for the Calculation of PFC Emissions from Aluminium Production (Tier 2 Methods), and 3.10, Default Emission Factors and Uncertainty Ranges for the Calculation of PFC Emissions from Aluminium Production (by Technology Type), provide estimates of uncertainty associated with emission factors for Tier 1 and Tier 2 methods. The method used to derive these values was a combination of classical statistics (two-sigma estimates) and expert judgement. Uncertainty for the Tier 1 method default factors is significantly higher than the Tier 3 and Tier 2 methods because smelter-specific operating conditions are not reflected in these estimates.

The uncertainty associated with AEF and AED or AEO, when measured, is expected to be low but will depend on computer scan rates (e.g. long scan rates will yield higher uncertainties) and data collection systems at each site.

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[20] If the Tier 3b method is being used, expert judgement should be used to determine when a significant change in operations or technology at a smelter will require development of a new smelter-specific slope coefficient.

3.3.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving.

Some examples of specific documentation and reporting relevant to this source category are provided below.

It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced.

To improve transparency, it is *good practice* to report emissions estimates for PFCs from aluminium production separately from other source categories. Additionally, it is *good practice* that CF_4 and C_2F_6 emissions are reported separately on a *mass basis*, as well as in CO_2-equivalent. [21]

Good practice methods require accurate anode effect frequency (AEF) and anode effect duration (AED) data for all cell types except Pechiney technology that requires instead accurate overvoltage (AEO) data. Statistical error estimates for AEF and AED or AEO should be reported.

It is *good practice* to archive at the company level the following information on the computer control system that will be included in statistical error estimates:

(i) AE trigger voltage; the voltage that defines the start of an AE;

(ii) AE termination voltage; the voltage that defines the end of an AE;

(iii) Scan rate; the frequency with which the cell voltage is measured;

(iv) Voltage averaging period; the period of time used to calculate the average voltage that is compared to the trigger and termination voltages.

The supporting information necessary to ensure transparency in reported emissions estimates is shown in Table 3.11, Good Practice Reporting Information for PFC Emissions from Aluminium Production by Tier, below.

Much of the production and process data are considered proprietary by operators, especially where there is only one smelter in a country. It is *good practice* to exercise appropriate techniques, including aggregation of data, to ensure protection of confidential data.

TABLE 3.11
GOOD PRACTICE REPORTING INFORMATION FOR PFC EMISSIONS FROM ALUMINIUM PRODUCTION BY TIER

Data	**Tier 3**	**Tier 2**	**Tier 1**
Annual production by smelter (by technology)	x	x	x
Anode Effect minutes per pot day (non Pechiney cells)	x	x	
Anode Effect Overvoltage (mV/cellday) (Pechiney cells)	x	x	
Emission coefficients	x	x	
Emission factor	x	x	x
GWPs	x	x	x
Supporting documentation	x	x	x

3.3.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, Section 8.7, Source Category-specific QC

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[21] According to *good practice* the GWPs used should be consistent with the *Guidelines for the preparation of national communications by Parties included in Annex I to the Convention, Part I: UNFCCC reporting guidelines on annual inventories* (*UNFCCC Guidelines*).

Procedures (Tier 2), and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

Additional procedures specific to aluminium production are outlined below:

Comparison of emission factors

Inventory agencies should check if the estimated emission factors are within the range of default emission factors provided for the Tier 1 method. If the emission factors are outside of this range, they should assess and document the smelter-specific conditions that account for the differences. It may be necessary to repeat measurements for validation purposes.

Plant-specific data check

The following plant-specific data is required for adequate auditing of emissions estimates:

- Production data;
- Process data records;
- Calculations and estimation method;
- List of assumptions;
- Documentation of sampling, measurement method, and measurement results.

If emission measurements from individual plants are collected, inventory agencies should ensure that the measurements were made according to recognised national or international standards. QC procedures in use at the site should be directly referenced and included in the QC plan. If the measurement practices were not consistent with QC standards, the inventory agency should reconsider the use of these data.

Verification of emissions estimates

Global atmospheric measurements of CF_4 and C_2F_6 concentrations can provide an upper limit on the total global emissions of PFCs from all source categories (Harnisch *et al.*, 1998). This can be used to check emissions estimates across the international aluminium production source category and potentially to evaluate the consistency of emission factors and coefficients. While it may be feasible to cross check emissions estimates from this source category by external measurements of plumes from smelters, the procedures for doing this are impractical, given the current state of technology, and are not required under *good practice*.

3.4 SF_6 EMISSIONS FROM MAGNESIUM PRODUCTION

3.4.1 Methodological issues[22]

In the magnesium industry, SF_6 is used as a cover gas in foundries to prevent oxidation of molten magnesium. It is assumed that all SF_6 used as cover gas is emitted to the atmosphere. It is *good practice* in inventory preparation in estimating emissions of SF_6 from use in the magnesium industry to consider, in a disaggregated way if possible, all segments of the industry using SF_6. These segments include primary magnesium production, die casting, gravity casting, and reprocessing (secondary production). It is *good practice* to assess other magnesium production processes that use and emit SF_6.

CHOICE OF METHOD

The choice of a *good practice* method will depend on national circumstances. The decision tree (see Figure 3.6, Decision Tree for SF_6 Emissions from Magnesium Production) describes *good practice* in adapting the methods in the *IPCC Guidelines* (Vol. 3, Section 2.13.8, SF_6 Used in Aluminium and Magnesium Foundries) to these country-specific circumstances. The *IPCC Guidelines* describe a general equation for calculating SF_6 emissions from magnesium that is the basis for all the methods described:

EQUATION 3.12

$$\text{Emissions of } SF_6 = \text{Consumption of } SF_6 \text{ in Magnesium Smelters and Foundries}$$

The most accurate application of this equation requires collecting direct data on SF_6 consumption from all individual users of the gas in the magnesium industry because these figures reflect apparent consumption rather than emissions. Consumption is defined as the use of SF_6 as a cover gas. In the absence of direct data, it is *good practice* to obtain estimates through a top-down method using production data and emission factors relevant to the various manufacturing processes. In cases where the data on direct use are incomplete, it is *good practice* to use a hybrid method that uses direct data where available, and production-based emission factors to complete the estimate. A hybrid approach is preferable to relying solely on the top-down approach.

If no direct data are available, an alternative but a less accurate method is to estimate the share of annual national SF_6 consumption attributable to the magnesium industry. This requires collecting annual data on national SF_6 sales and assumes that all SF_6 gas sold to the magnesium industry is emitted within the year.

CHOICE OF EMISSION FACTORS

Since the direct reporting method assumes that all SF_6 consumption is emitted, there is no need to use emission factors or coefficients when SF_6 consumption data are available. When complete reported data are not available it is *good practice* to obtain emission factors for each segment of the industry consistent with the decision tree in Figure 3.6, Decision Tree for SF_6 Emissions from Magnesium Production. These emission factors should relate SF_6 emissions to magnesium production at the same disaggregated level as the available activity data (e.g. national, sub-national). National emission factors based on plant measurements are preferable to international default factors because they reflect conditions specific to the country. Such information may be accessible through industry associations, surveys or studies.

The *IPCC Guidelines* do not provide default emission factors for SF_6 from magnesium. Under recommended conditions for die-casting, the consumption rates are about 1 kg SF_6 per tonne magnesium produced or smelted (Gjestland, 1996). It is *good practice* to use this value in the absence of better information. This default value is quite uncertain, however. For example, one diecasting industry survey showed a wide range of SF_6 consumption rates, from 0.1 to 10 kg SF_6 per tonne magnesium produced (Palmer, 1999).

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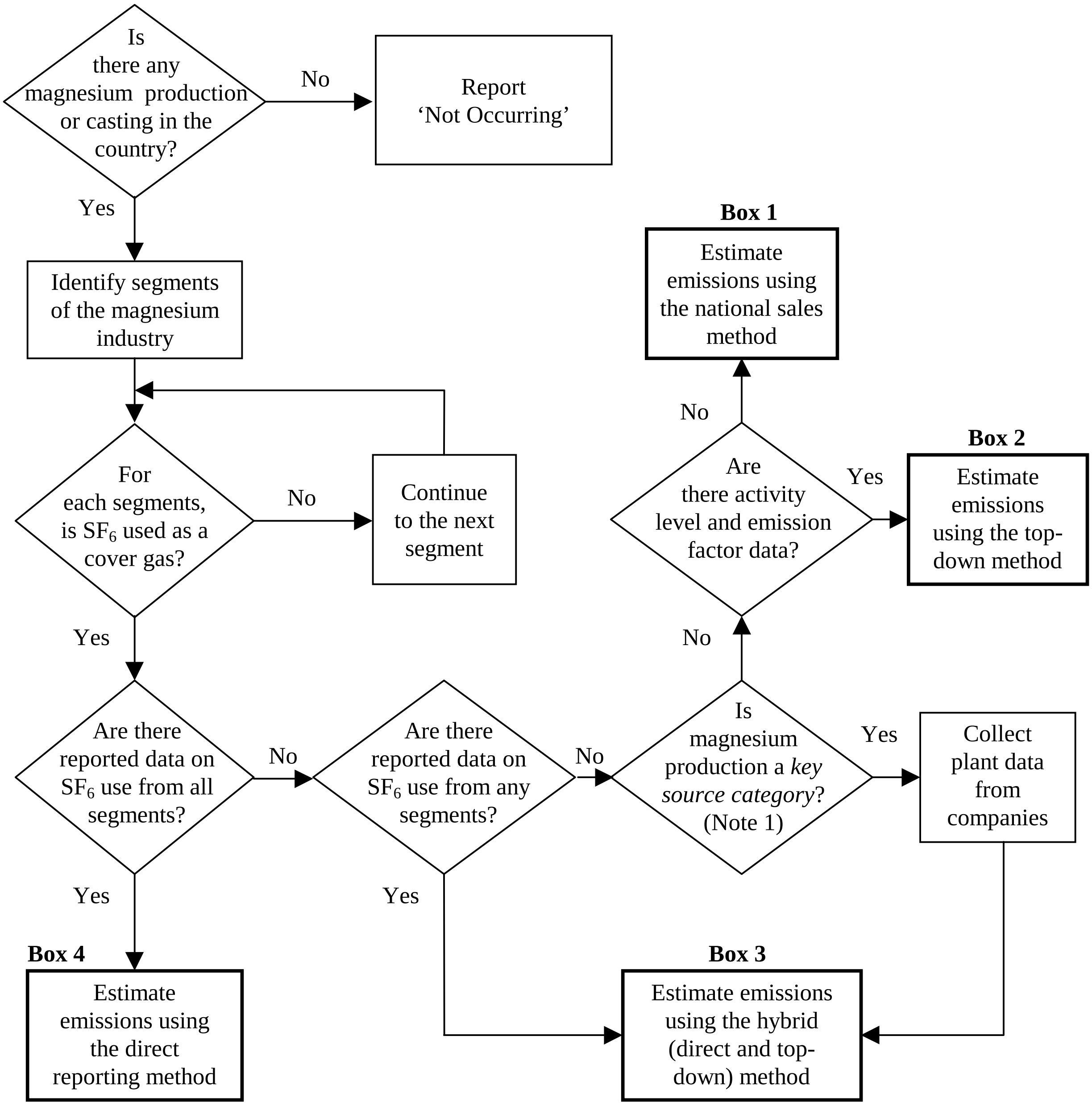
[22] SF_6 is sometimes used in the aluminium industry as a cover gas or for other purposes, and is assumed to be inert. The emissions of SF_6 are therefore assumed to be equal to consumption, and can be estimated using a consumption-based approach similar to the consumption-based method for magnesium production. The emission factors and the national sales method as discussed for magnesium production are not applicable to SF_6 used in aluminium production.

Figure 3.6 Decision Tree for SF_6 Emissions from Magnesium Production



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

CHOICE OF ACTIVITY DATA

With the direct-reporting method, the activity data are SF_6 consumption totals from each plant. Magnesium production data are necessary for those plants that do not report SF_6 consumption data. Where there is some direct reporting of SF_6 use, it is *good practice* to assess the share of the total segment's magnesium production that is represented by the plants that are directly reporting SF_6 data. For the other plants, it is *good practice* to use production-based estimates of emissions.

To the maximum possible extent, it is *good practice* to disaggregate production data into segments (e.g. primary production, die casting, gravity casting) using SF_6 within the magnesium industry to make full use of segment-specific emission factors. Where disaggregated data are not available, more aggregated production data, possibly combining output from several different processes, may be used to provide an estimate. In the absence of SF_6 consumption data or magnesium production data, the alternative is to collect annual national data on SF_6 sales to the magnesium industry. This data could come directly from SF_6 producers or from national statistics. It is *good practice* to consider data on consumption by other industries that use SF_6 (e.g. electrical equipment) when estimating the share consumed by the magnesium industry.

COMPLETENESS

Incomplete direct reporting or activity data should not be a significant issue for primary production. There is a small number of primary magnesium producers that are generally well known and keep good records. Completeness issues generally arise in the casting segments, where facilities are more widely distributed, and have a wide range of capacities and technologies. Some plants may supply to niche markets that are not captured by national data sets. The inventory agency should confirm the absence of estimates for these smaller industry segments rather than simply assuming they do not occur. It is also *good practice* to undertake periodic surveys of the industry and establish close links with the local industry associations to check completeness of estimates.

DEVELOPING A CONSISTENT TIME SERIES

There may be issues of data availability associated with establishing historical emissions, particularly when implementing a direct reporting approach. It is *good practice* to use historical SF_6 data where available, but SF_6 purchase records for previous years may not be archived by magnesium manufacturers.

In the absence of such data, a default approach of multiplying activity data by an assumed emission factor may be used. In some cases, emission factors may decrease over time due to environmental awareness, economic factors, and improved technologies and practices. *Good practice* is to assess the appropriate historical emission factors following the guidance in Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques. In some cases, historical production data may not be available due to lack of initial records or changes in the structure of the industry in the intervening period. In this case, international production data may be used or, if this too is unavailable, a general relationship between national economic activity and magnesium production. To ensure consistency over time, it is *good practice* to recalculate emissions estimates using previously used and new methods to ensure that any trends in emissions are real and not caused by changes in the estimation methodologies. *Good practice* is to document assumptions in all cases and archive them at the inventory agency.

UNCERTAINTY ASSESSMENT

At the plant level, there is a very low uncertainty associated with plant SF_6 use data, since SF_6 use is measured easily and accurately from purchase data. (An uncertainty estimate of less than 5% is usually appropriate for directly reported data.) There is some uncertainty associated with the assumption that 100% of the SF_6 used is emitted. Anecdotal evidence suggests that, under certain extreme conditions, a minor portion of SF_6 applied may react or decompose in the process. For inventory purposes, however, until further peer-reviewed research work clarifies this effect, the assumption is that all SF_6 used as a cover gas is emitted. Uncertainties are much higher where plant data are not available and emissions could be much higher or lower than indicated by use of the IPCC defaults, as already indicated

At the national inventory level, the accuracy of magnesium production activity data is comparable to that of other national production statistics (i.e. ±5%). Additional uncertainty is introduced through estimating the share of production not reporting directly. Aggregating production from different segments and using aggregated emission factors also introduces uncertainty. For example, national data from casting operations may not be segregated into die-casting and gravity casting segments despite their potentially different SF_6 emission rates. Estimating SF_6 emissions on the basis of sales to the magnesium industry each year is highly uncertain, because SF_6 may be purchased in bulk quantities and not used until later years. The uncertainty in this case will be bounded by the total sales data.

3.4.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal

Documentation and Archiving. It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced.

To improve transparency, it is *good practice* to report emissions estimates from this source category separately by industry segment.

The following additional information can provide a reasonable degree of transparency in reporting:

Direct Reporting

- Number of plants reporting;
- Magnesium and magnesium products production;
- SF_6 emissions;
- Emission factor data (and reference).

National SF_6 sales-based estimate of potential emissions

- National SF_6 consumption (and reference);
- Assumptions for allocating SF_6 used to magnesium;
- Estimate of percentage of national SF_6 used in magnesium (and reference);
- Any other assumptions made.

In most countries, the magnesium industry will be represented by a small number of plants. In this industry, the activity level data and SF_6 emissions (that are directly related to activity levels) may be considered confidential business information and public reporting may be subject to confidentiality considerations.

3.4.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1 Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks, as outlined in Chapter 8.7, Source Category-specific QC Procedures (Tier 2), and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from *this source category*. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

Additional procedures specific to magnesium production are outlined below:

Comparison of emissions estimates using different approaches

If emissions were calculated using data from individual plants (bottom-up approach), inventory agencies should compare the estimate to emissions calculated using national magnesium production data or national SF_6 consumption (top-down approach). The results of the comparison should be recorded and any discrepancies should be investigated.

Review of plant-level data

The following plant-specific information should be archived to facilitate independent review:

- SF_6 consumption or magnesium production (where factors are used);
- Plant-level QA/QC results (including documentation of sampling, measurement method, and measurement results for plant level data);
- Results of QA/QC conducted by any integrating body (e.g. industry association);
- Calculations and estimation method;
- Where applicable, a list of assumptions in allocating national SF_6 usage or production to plant level.

Inventory agencies should determine if national or international measurement standards were used for SF_6 consumption or magnesium production data at the individual plants. If standard methods and QA/QC were not followed, then they should reconsider the use of these activity data.

Review of national activity data

QA/QC activities associated with the reference to magnesium production data should be evaluated and referenced. Inventory agencies should check if the trade association or agency that compiled the national production data used acceptable QA/QC procedures. If the QA/QC procedures are deemed acceptable, inventory agencies should reference the QC activity as part of the QA/QC documentation.

Assessment of emission factors

Where country-specific SF_6 factors are used, inventory agencies should review the level of QC associated with the underlying data. Although there is no IPCC default emission factor, *good practice* is that the inventory agency cross-check national level default factors against plant-level factors to determine their representativeness.

Peer review

Inventory agencies should involve magnesium industry experts in a thorough review of the inventory estimate, giving consideration to potential confidentiality issues. Historical production data may be less sensitive to public disclosure than current data and could be utilised for an external peer review of plant level emissions.

Verification of SF_6 emissions data

Inventory agencies should sum the amount of SF_6 used by different industrial sectors (e.g. magnesium, electrical equipment) and compare this value with the total usage of SF_6 in the country, obtained from import/export and production data. This provides an upper bound on the potential emissions.[23]

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[23] It may not always be the case that such aggregated consumption data will provide an upper limit on emissions. It is possible, depending on the national characteristics of the SF_6 consuming industry that in some years actual emissions of SF_6 may be greater than consumption of SF_6. For instance, consumption in die casting of magnesium may be very low, there may not be much semiconductor manufacturing, but a considerable bank of SF_6 in electrical equipment may have evolved through the years. In this case, leakage from bank combined with emissions resulting from decommissioning of equipment may lead to actual emissions that exceed consumption of SF_6 (potential emissions). See also Table 3.12, Default Emission Factors for SF_6 Emissions from Electrical Equipment – Tier 2 (fraction of SF_6/yr).

3.5 EMISSIONS OF SF_6 FROM ELECTRICAL EQUIPMENT AND OTHER SOURCES

3.5.1 Electrical equipment

3.5.1.1 Methodological issues

Sulfur hexafluoride (SF_6) is used for electrical insulation, arc quenching, and current interruption in equipment used in the transmission and distribution of electricity. Most of the SF_6 used in electrical equipment is used in gas insulated switchgear (GIS) and circuit breakers, though some SF_6 is used in high voltage gas-insulated transmission lines and other equipment. SF_6 emissions from electrical equipment are the largest global source category of SF_6 emissions.

CHOICE OF METHOD

The choice of *good practice* method will depend on national circumstances. The decision tree, Figure 3.7, Decision Tree for SF_6 from Electrical Equipment, describes *good practice* in adapting the methods in the *IPCC Guidelines* to these country-specific circumstances.

The *IPCC Guidelines* include methods for estimating both potential (Tier 1 method) and actual (Tier 2 method) emissions of SF_6 from electrical equipment. This section describes *good practice* for using the Tier 1 method and two variants of the current Tier 2 method. Three variants of a more accurate approach (termed Tier 3 method) are also described. Emissions estimates developed using the Tier 3 method will be the most accurate. Estimates developed using the Tier 1 method will be the least accurate because these figures reflect apparent consumption rather than emissions.

Tier 3 Method – Mass-balance approach

The Tier 3 method is the most accurate approach for estimating actual emissions of SF_6 from electrical equipment. It is a mass-balance approach that tracks the amount of new SF_6 introduced into the industry each year. Industry uses some of this newly purchased SF_6 to replace leaked gas that escaped to the atmosphere the previous year. The remainder of the new SF_6 is used to fill an increase in total equipment capacity, and thus does not replace leaked gas. To develop an accurate estimate, therefore, this approach distinguishes between the SF_6 used to replace emitted gas and SF_6 used to increase total equipment capacity or replace destroyed gas.[24]

The main advantages of this approach are: (i) equipment manufacturers and facilities can readily track the required information, and (ii) it does not depend on global default emissions factors that are subject to considerable uncertainty. This tier can be implemented at different levels of aggregation depending on data and resource availability. The most accurate approach is to estimate emissions from each lifecycle stage of the equipment at the facility level (Tier 3a method). Alternatively, the life cycle calculation may be bypassed and emissions can be estimated at the aggregate facility level (Tier 3b method) or at the country level (Tier 3c method). Inventory agencies are encouraged to use the most detailed approach that is practical, and to use alternative estimation methods to check the results.

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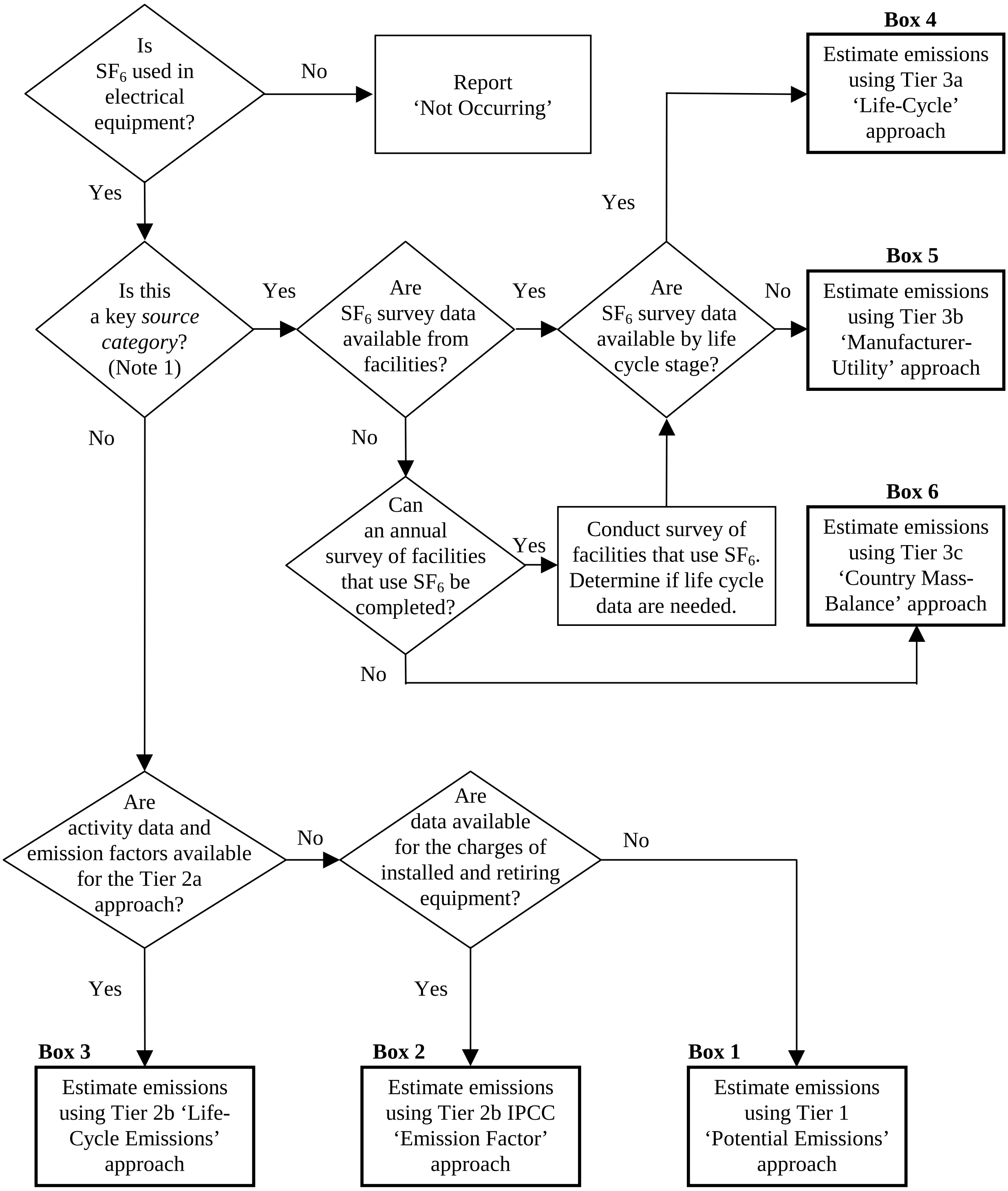
[24] For example, suppose that 100 circuit breakers are retired in a country in a certain year, and 150 new circuit breakers (with the same average charge size as the retiring breakers) are installed. In this case, the manufacturers or users of the circuit breakers in that country must purchase at least enough gas to charge 50 circuit breakers, even if they recover all of the gas from the retiring 100 circuit breakers and use it to fill 100 of the breakers that replace them. The gas used to charge the 50 'extra' circuit breakers is used to fill an increase in equipment capacity, and does not replace emitted gas. Some gas that is contaminated during inspection is destroyed using thermal destruction methods.

Figure 3.7 Decision Tree for SF_6 from Electrical Equipment



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Tier 3a Method – Emissions by life cycle stage of equipment

This approach is useful for inventory agencies or facilities that, in addition to estimating their total emissions of SF_6 from electrical equipment, wish to determine how and when such emissions occur during the lifecycle of the equipment. Information on how and when emissions occur is important for focusing mitigation efforts where they will be most effective. The method includes separate equations for each phase of the lifecycle of equipment, including equipment manufacture, installation, usage, and disposal. Ideally, data are obtained for every equipment manufacturer and utility in the country, and the emissions of all manufacturers and utilities are summed to develop the national estimate. The basic equation is:

EQUATION 3.13

$$\text{Total Emissions} = \sum \text{Manufacturing Emissions} + \sum \text{Installation Emissions} + \sum \text{Use Emissions} + \sum \text{Disposal Emissions}$$

In the above equation, national emissions for each phase are equal to the sum of all equipment manufacturers' emissions for each phase.

Each *equipment manufacturer's* emissions can be calculated in three steps:

(i) Collect the data on the net decrease in their annual SF_6 inventory on hand. (Note that if the inventory increases, this will be a negative number);

(ii) Add the amount of SF_6 obtained during the year (including any SF_6 purchased from producers or distributors, any SF_6 returned from equipment users, and any SF_6 returned by users after recycling);

(iii) Subtract the amount of SF_6 transferred to others during the year (including the amount of SF_6 in new equipment delivered to customers, the amount delivered to equipment users in containers, and the amount returned to SF_6 producers, sent to recycling firms, or destroyed).

Equipment installation emissions can be estimated by subtracting the nameplate capacity[25] of all new equipment filled from the actual amount of SF_6 used to fill new equipment.

Equipment use emissions are determined by the amount of SF_6 used to service equipment. If SF_6 is being recovered from equipment before servicing and returned after servicing, it is important that this amount not be included in the estimate.

Emissions from *equipment disposal* are estimated by subtracting the amount of SF_6 recovered from retired equipment from the nameplate capacity of the retired equipment and also subtracting the amount of SF_6 destroyed.

Tier 3b Method – Manufacturer and utility-level mass-balance method

If data for estimating emissions from lifecycle stages are unavailable, emissions can be estimated by tracking overall consumption and disposal of SF_6 for all utilities and manufacturers. Beginning with the equation for Tier 3a method, installation, use, and disposal emissions are aggregated into the category of *utility emissions*. The equation presented in Tier 3a method is thus simplified to:

EQUATION 3.14

$$\text{Total Emissions} = \sum \text{Manufacturer Emissions} + \sum \text{Utility Emissions}$$

Using this approach, *equipment manufacturer* emissions are estimated as for the Tier 3a method.

Utility emissions are equal to the sum of emissions from all utilities. Each utility's emissions can be calculated through the following seven steps:

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[25] Nameplate capacity – The 'nameplate capacity' is the quantity of SF_6 required to fill a piece of equipment so that it will function properly. It may also be referred to as the 'charge' and is generally indicated by the nameplate of the equipment. The 'total nameplate capacity' of all the equipment in a country or facility is the sum of the proper, full charges of all the equipment in use in that country or facility.

(i) Determine the net decrease in the amount of SF_6 stored in containers over the reporting year;

(ii) Add the amount of SF_6 purchased from producers/distributors and equipment manufacturers, including the amount of SF_6 contained in purchased equipment;

(iii) Subtract the amount of SF_6 returned to suppliers;

(iv) Add SF_6 returned after recycling;

(v) Subtract any SF_6 sent to recycling firms, sold to other entities, or destroyed by the utility or installation;

(vi) Add the nameplate capacity of retired equipment;

(vii) Subtract the nameplate capacity of new equipment.

Tier 3c Method – Country-level mass-balance method

In some cases, it may be impractical for inventory agencies to obtain emissions data from all equipment manufacturers and utilities, or such data may be incomplete. In this case, a national level estimate can be developed based on annual national sales of SF_6 into the electrical sector (current and historical), equipment imports and exports, SF_6 destruction, and, if possible, country-specific equipment lifetime assumptions. The basic equation is:

EQUATION 3.15

$$\text{Emissions} = \text{Annual Sales} - (\text{Net Increase in Nameplate Capacity}) - (SF_6 \text{ Destroyed})$$

Annual sales are equal to new SF_6 for filling or refilling electrical equipment, both in bulk and in equipment itself.

Net increase in nameplate capacity can be calculated through the following steps:

(i) Collect data on the nameplate capacity of new equipment, including both equipment that is filled in the factory before shipment and equipment that is filled after installation;

(ii) Subtract the nameplate capacity of all retiring equipment.

It is *good practice* to include the quantity of SF_6 destroyed from all electrical equipment in *SF_6 destroyed.*

Tier 2a Method – Life-cycle emission factor approach

If only limited data are available on annual sales of SF_6 to equipment manufacturers and utilities, emissions can be estimated for each stage of the lifecycle of the equipment, using emission factors that are unique to each stage. *Good practice* is to use the following equation:

EQUATION 3.16

$$\text{Total Emissions} = \text{Manufacturing Emissions} + \text{Installation Emissions} + \text{Use Emissions} + \text{Disposal Emissions}$$

Manufacturing emissions are estimated by using emission factors based on the amount of SF_6 purchased by equipment manufacturers, or the nameplate capacity of new equipment charged.

Similarly, *equipment installation* emissions are estimated using either purchase-based or nameplate-based emission factors. This will require data on either the amount of SF_6 purchased by utilities for new equipment or the nameplate capacity of new equipment charged by utilities (not equipment manufacturers). In some cases, the nameplate capacity of new equipment may be known, but not the fractions of this capacity filled by manufacturers versus utilities. Under these circumstances, a single ‘Manufacturing/Installation Emission Factor’ can be multiplied by the total nameplate capacity of new equipment.

Equipment use emissions are estimated by multiplying the total nameplate capacity of installed equipment by a ‘Use Emission Factor’. The ‘use emission factor’ includes emissions due to leakage, and servicing and maintenance that are typically carried out every 12 years.

Finally, *equipment disposal* emissions are estimated by multiplying the nameplate capacity of retiring equipment by the assumed fraction of SF_6 left in equipment at the end of its life. If SF_6 is being recovered, *good practice* is to adjust the resulting estimate to reflect recovery, by multiplying by (1 – the recovery factor). The default recovery factor is zero. Other factors should be country-specific and determined at the site-level.

Tier 2b Method – IPCC default emission factors

If inventory agencies only have information on the total charges of installed and retiring equipment, the emission factors can be applied at a national level, as described in the *IPCC Guidelines*:

EQUATION 3.17

Emissions of SF_6 in year t = (2% of the Total Charge of SF_6 Contained in the Existing Stock of Equipment of Operation in year t) + (95% of the Nameplate Capacity of SF_6 in Retiring Equipment)

The first term of the equation estimates leakage and maintenance losses as a fixed percentage of the total charge (e.g. 2%). The existing stock of equipment in each year includes all equipment installed in that year in addition to previously installed equipment that is still in use. The second term calculates emissions from retiring equipment (e.g. after a lifetime of 30 years) and assumes that the minimum charge is 90%. Recent experience indicates that the default assumption of 70% in the *IPCC Guidelines* underestimates retiring emissions, because equipment does not function below 90% capacity and will be refilled during its lifetime (Bitsch, 1999b). Thus, inventory agencies using this approach are encouraged to review the applicability of the emissions factors in the equation and use country-specific emission factors if appropriate – especially with respect to implemented recycling procedures.

Tier 1 Method – Potential approach

The simplest estimation method in the *IPCC Guidelines* estimates potential emissions of SF_6 from all uses by equating emissions to total consumption of SF_6:

EQUATION 3.18

Potential SF_6 Emission = Production + (Imports – Exports) – Destruction

Inventory agencies will need to determine how much of the total SF_6 is sold to utilities and equipment manufacturers. This can be done directly (by obtaining data on such sales) or indirectly (by obtaining data on sales for other uses). The direct approach uses the following equation:

EQUATION 3.19

SF_6 Emissions from Electrical Equipment = Sales of SF_6 to Equipment Manufacturers + Sales of SF_6 to Utilities + (SF_6 in Imported Equipment – SF_6 in Exported Equipment)

The indirect approach is as follows:

EQUATION 3.20

SF_6 Emissions = Production + (Imports – Exports) – Destruction
– Consumption by Other SF_6 Uses (i.e. Mg Smelting, Semiconductor Manufacturing, Other Uses)

Both equations implicitly assume that all SF_6 sold into the electrical sector replaces released gas, when in fact some of that SF_6 may be used to fill a net increase in the nameplate capacity of installed equipment or to replace destroyed gas. *Good practice* considers estimates developed using the Tier 1 method an upper bound.

CHOICE OF EMISSION FACTORS

As of the variability of emissions rates from region to region, inventory agencies using the Tier 2 method are encouraged to develop and use their own emissions factors. Surveying a representative sample of equipment manufacturers and utilities within the country is an effective way to develop such factors.

Tier 2a Method

Emission factors for the Tier 2a method are developed based on data collected from representative manufacturers and utilities that track emissions by life cycle stage, essentially using the Tier 3a method at their facilities for one year. Total emissions from the survey of manufacturers are summed and then divided by the surveyed facilities' new equipment capacity. This emission factor can then be applied to the manufacturing sector as a whole, using national new equipment capacity.

Tier 2b Method

For developing emission factors for the Tier 2b method, it is *good practice* for surveyed utilities to track their total consumption of SF_6 for refilling of equipment, the total nameplate capacity of their equipment, the quantity of SF_6 recovered from retiring equipment, and the nameplate capacity of their retiring equipment. It is *good practice* to sum emissions from the servicing and disposal of equipment across surveyed utilities. The resulting total emissions estimates for servicing and disposal are then divided by the surveyed utilities' total installed equipment capacity or by their total retiring equipment capacity, respectively, to calculate emission factors for use and for disposal.

The *IPCC Guidelines* do not provide default emission factors for each lifecycle stage, but suggested factors have been developed for some regions based on recent research. These factors are shown in Table 3.12, Default Emission Factors for SF_6 Emissions from Electrical Equipment – Tier 2 (fraction of SF_6/yr).

TABLE 3.12
DEFAULT EMISSION FACTORS FOR SF_6 EMISSIONS FROM ELECTRICAL EQUIPMENT – TIER 2 (FRACTION OF SF_6/YR)

Phase	Manufacturing		Installation		Use		Retired Equipment		
Region	**before 1996**	**Since 1996**	**before 1996**	**Since 1996**	**before 1996**	**Since 1996**	**Lifetime**	**Remaining**	**Recovery**
Europe[b]	0.15	0.06	NA	0.06	NA	NA	NA	NA	NA
Japan[a]	0.3	0.3	NA	NA	0.001	0.001	NA	NA	NA
Global[c]	NA	NA	0.15	0.15	0.05	0.02	30 years	0.95	NA

[a] Emission factors of use phase are only for natural emissions (Denki Kyodo Kenkyu, 1998 and Chemical Products Council, 1999).
Sources:
[b] Bitsch, 1999a.
[c] Olivier and Bakker, 2000.
NA = not available.

CHOICE OF ACTIVITY DATA

The guidance given below for the Tier 3 methods applies to the same parameters when they are used in the Tier 2 and Tier 1 methods. The only unique requirement for the Tier 2 method is the *total nameplate capacity* of equipment. Nameplate capacity may be estimated either by surveying utilities directly, or by surveying equipment manufacturers regarding their sales of equipment over the lifetime of the equipment (e.g. for the last 30 years).

Tier 3a Method – Emissions by life cycle stage

Since Tier 3a method does not rely on emissions factors, the quality of the estimate depends on the accuracy and completeness of surveyed activity data. The data should be available directly from individual manufacturers, or through manufacturer associations.

***Equipment manufacturing*:** A complete survey of all equipment manufacturers includes, at a minimum, data on the movement of SF_6 through the production and assembly phase, and data on handling emissions of the gas after delivery to manufacturing sites. The survey should request enough information to provide a full accounting of SF_6 consumption and losses during the production phase. Annual *mass balance tables* can be used to estimate how much SF_6 gas is lost due to emission releases and what fraction this is of nominal SF_6 content of total electrical equipment produced.

If survey data are not available for all manufacturers, alternative methods can be considered (e.g. based on extrapolation of production capacity). *Good practice* is to use survey data as far as possible and only supplement them with extrapolative approaches where survey data is not available. For guidance on extrapolating when data are not available, see Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques.

***Equipment installation*:** All utilities and other users of electrical equipment should track and record the nameplate capacity of the equipment that is filled. Utilities should also track the amount of SF_6 that is used to fill equipment by weighing cylinders before and after filling operations, and tracking any SF_6 that is already in the shipped equipment (e.g. to maintain a slight positive pressure during shipment). If filling is performed by the equipment manufacturer rather than by the utility, then the manufacturer may provide this information to the utility.[26] Where there are gaps and omissions in the survey, it is possible to use estimates of SF_6 stock additions and default emission rates for installation and set-up procedures.

***Equipment use*:** It is *good practice* to calculate the quantity of SF_6 used to refill equipment by weighing cylinders before and after filling operations.

***Equipment disposal*:** The quantity of SF_6 recovered from equipment may be calculated by weighing recovery cylinders before and after recovery operations. Data on disposal should include all equipment, including imported equipment.

Tier 3b Method – Manufacturer and utility-level mass-balance method

***Equipment manufacturers*:** Same as for Tier 3a, above.

***Utilities*:** To collect the information necessary to use the Tier 3b method, a survey of all utilities is required. *Good practice* is to survey industrial sites, military installations, and other non-utility sites that use significant amounts of SF_6 in electrical equipment. Some, but not all, of the above information may also be obtained from equipment manufacturers.

If the utility does not perform all of its own installation, maintenance, and disposal of equipment, persons who provide these services should provide data to the utility (e.g. the quantity of gas used to refill equipment, if this gas did not come from the utility's own inventory). A full accounting of SF_6 emissions associated with handling and filling losses needs to be collected. This accounting can be based on annual mass balance tables that include the amount of SF_6 already contained in the equipment when shipped to the site. The party responsible for tracking SF_6 handling and filling operations needs to be identified, since this can vary from site to site.

Tier 3c Method – Country-level mass-balance method

***Annual sales*:** Chemical manufacturers or importers or both should be able to supply the most complete data. If information from chemical manufacturers is not available, it is *good practice* to contact both equipment manufacturers and utilities to ensure complete data on SF_6 used to fill both new and existing equipment.

***Nameplate capacity of new and retiring equipment*:** Nameplate capacity can be estimated using one of the following data sources: (1) information from equipment manufacturers/importers on the total nameplate capacity of the equipment they manufacture or import and export, (2) information from utilities on the total nameplate capacity of the equipment they purchase and install each year, or (3) information from chemical manufacturers/importers on their sales of SF_6 to equipment manufacturers. The first two data sources are preferable to the third, because gas sales to new equipment manufacturers will differ to some extent from the nameplate capacity of new equipment. In estimating the nameplate capacities of new and retiring equipment, inventory agencies should include the nameplate capacity of imported equipment and exclude the nameplate capacity of exported equipment. (See Section 3.7.4, Stationary Refrigeration Sub-source Category, Box 3.4, Accounting for Imports and Exports of Refrigerant and Equipment, for a full discussion of how to treat imports and exports in estimating these quantities.)

In the case of retiring equipment, capacity or sales information should be historical, starting in the year when the current year's retiring equipment was built. The default value for the lifetime of electrical equipment is 30 years. If information on the total nameplate capacity of retiring equipment is not available, it can be estimated from new nameplate capacity, using the estimated annual growth rate of equipment capacity. In estimating the growth rate,

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[26] The quantity already in shipped equipment may be calculated by multiplying the internal volume of the equipment by the density of SF_6 at the shipment pressure, or by multiplying the nameplate capacity of the equipment by the ratio of the shipping pressure to the nameplate pressure, in absolute terms (e.g. Pa or psi). In theory, equipment that arrives at the utility already completely filled does not need to be included in this calculation, because the quantity of SF_6 inside the equipment will be identical to the nameplate capacity, and the two will simply cancel. However, utilities are encouraged to track the total nameplate capacity of the equipment they install, because this quantity is useful for calculating emissions using the Tier 3 and Tier 2 methods and for understanding emissions during equipment use.

it is *good practice* to consider both the number of pieces of equipment sold each year and the average nameplate capacity of the equipment.[27]

The following equation can be used to estimate retiring nameplate capacity, if this information is not available directly:

EQUATION 3.21

$$\text{Retiring Nameplate Capacity} = \text{New Nameplate Capacity} \; / \; (1 + g)^L$$

Where:

L = equipment lifetime

g = rate of growth

According to a 1997 survey, the average annual growth rate of SF_6 sales to equipment manufacturers between 1991 and 1996 was 6.7%, while the average rate of growth between 1986 and 1996 was 5.3% (Science and Policy Associates, 1997). In the absence of country-specific information, it is *good practice* to use a default factor of 6%.

Quantity destroyed**:** The amount of SF_6 destroyed can be estimated using information from electrical equipment manufacturers, utilities, chemical manufacturers, or destruction facilities. It is necessary to ensure that the quantities of SF_6 reported as destroyed do not include quantities from sources other than electrical equipment.

COMPLETENESS

Completeness for this source category requires accounting for emissions both at utility facilities and during the manufacture of electrical equipment. Where Tier 3 methods are used, completeness requires that all SF_6 users (manufacturers and utilities) be identified.

In the manufacturing sector, this requires assessing emissions from:

- GIS and circuit breaker manufacturers;
- Manufacturers of high voltage gas-insulated transmission lines, substations (mini-stations) and transformers;
- Minor SF_6 users, including medium voltage equipment manufacturers and equipment remake manufacturers;
- SF_6 moving from producers and distributors to manufacturing facilities.

In the utility sector, this requires accounting for all SF_6 losses associated with:

- New electrical equipment installations;
- Leakage, refill and maintenance;
- Disposal of discarded electrical equipment.

It is *good practice* to identify and include industrial, military and small-utility applications if these are believed to contribute substantially to total emissions from this source category.

DEVELOPING A CONSISTENT TIME SERIES

When estimating emissions over a time series, it is necessary to consider SF_6 emissions associated with manufacturing and all installed equipment at utilities for the years of interest. Developing an accurate historical estimate for installed equipment thus requires information on the capacity and performance of equipment installed for 20 to 30 years preceding the years of interest.

On the manufacturing side, if historical data for developing base year emissions for 1990/1995 are not available, the top-down method calibrated to more accurate account balances for current years may be applied. Since SF_6 handling practices of equipment manufacturers may have changed substantially since 1995 (e.g. more gas is recovered), it is *not good practice* to apply current loss rates to historical estimates. Aggregate loss rates determined from global and regional sales and emission analyses may assist in providing an unbiased estimate for earlier years. It is *good practice* to recalculate emissions according to the guidance provided in Chapter 7,

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[27] While the number of pieces of equipment sold each year has generally grown, the average nameplate capacity has generally declined.

Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques, with all assumptions clearly documented.

In the utility sector, if historical data for the period 1970-1995 are unavailable, *good practice* is to develop estimates using the top-down method, and then calibrate as discussed above. Average leakage rates for new equipment, and the frequency of refill and routine maintenance all decreased from 1970 to 1995.[28] It is *good practice* not to apply current (post-1995) overall loss rates to historical years. Aggregate loss rates can be used in this case as well.

UNCERTAINTY ASSESMENT

When using Tier 3 methods, the resulting emissions estimates are likely to be more accurate than Tier 2 or Tier 1 methods, of the order of ±10%. If surveys are incomplete or only top-down consumption data are available, the associated uncertainty will be greater. Particular sources of uncertainty in the Tier 3 methods estimates may include:

- SF_6 exported by equipment manufacturers (either in equipment or separately in containers);
- SF_6 imported by foreign equipment manufacturers (either in equipment or in containers);
- SF_6 returned to foreign recycling facilities;
- Time lag between emissions and servicing;[29]
- Lifetime of the equipment.

The uncertainties in the default emission factors recommended for the Tier 2 method are shown in Table 3.13, Uncertainties for Default Emission Factors for SF_6 Emissions from Electrical Equipment. As the Tier 1 method estimates potential rather than actual emissions, Tier 1 estimates will have an uncertainty of the order of 100% or more in representing an estimate of actual emissions.

TABLE 3.13
UNCERTAINTIES FOR DEFAULT EMISSION FACTORS FOR SF_6 EMISSIONS FROM ELECTRICAL EQUIPMENT

Phase	Manufacturing		Installation		Use		Retired Equipment		
Region	**<1996**	**1996-**	**<1996**	**1996-**	**<1996**	**1996-**	**Lifetime**	**Remaining**	**Recovery**
Europe	±30%	±30%	NA	±30%	NA	NA	NA	NA	NA
Japan	±30%	±30%	NA	NA	NA	NA	NA	NA	NA
Global	Larger	Larger	±30%	±30%	±40%	±50%	±30%	±5%	NA

NA= not available.

Source: Olivier and Bakker (2000).

3.5.1.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving. It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced.

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[28] Standards for leakage from GIS are now 1%, but were as much as 3% prior to 1980. In addition, maintenance intervals have increased, from 3-5 years to 8 years for circuit breakers and about 12 years for GIS.

[29] The sales-based method is designed to yield a good estimate of the quantity of chemicals used to replace emitted chemicals in a given year. However, because some equipment may leak but nevertheless continue to run with less than a full charge, emitted chemicals are not always replaced during the year that it leaks. Thus, under some circumstances, the sales-based method may slightly either over or underestimate actual emissions. (The net effect of the time lag is to make emissions appear to occur later in the life of equipment than they actually do.) The frequency of servicing and the growth rate of the equipment stock should be investigated to ascertain the size of any error.

Some examples of specific documentation and reporting relevant to this source category ensuring transparency in reported emissions estimates are provided in Table 3.14, Good Practice Reporting Information for SF_6 Emissions from Electrical Equipment by Tier.

Confidentiality issues may arise where there are limited numbers of manufacturers or utilities. In these cases, aggregated reporting for the total electrical equipment sector, or even total national SF_6 applications, may be necessary. If survey responses cannot be released as public information, third party review of survey data may be necessary to support data verification efforts.

TABLE 3.14
GOOD PRACTICE REPORTING INFORMATION FOR SF_6 EMISSIONS FROM ELECTRICAL EQUIPMENT BY TIER

Data	Tier 3a	Tier 3b	Tier 3c	Tier 2a	Tier 2b	Tier 1
Annual sales of SF_6 to equipment manufacturers and utilities			X			X
Nameplate capacity of new equipment	X	X	X	X		
Nameplate capacity of existing equipment				X	X	
Nameplate capacity of retiring equipment	X	X	X	X	X	
SF_6 destroyed	X	X	X			X
SF_6 in inventory at beginning of year	X	X				
SF_6 in inventory at end of year	X	X				
SF_6 purchased by facility	X	X				
SF_6 sold or returned by facility	X	X				
SF_6 sent off-site for recycling	X	X				
SF_6 returned to site after recycling	X	X				
SF_6 used to fill new equipment	X					
SF_6 used to service equipment	X					
SF_6 recovered from retiring equipment	X					
Emission/recovery factors				X	X	
Documentation for factors, if country-specific				X	X	
Production of SF_6						X
Consumption of SF_6 by other uses						X
Imports of SF_6						X
Exports of SF_6						X

3.5.1.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

Additional procedures specific to electrical equipment are outlined below:

Comparison of emissions estimates using different approaches

Inventory agencies should sum the facility-level data used as part of a bottom-up method and cross-check the data against national level emissions calculated using the IPCC defaults (Tier 2b method) or potential emissions estimated using national apparent consumption data (Tier 1 method). The Tier 1 method can set an upper bound on the emissions that could be expected from the sum of the individual plants if the annual use of SF_6 containing equipment in these sources is increasing or stable. Tier 1 will underestimate the annual emissions if the trend of filling of new equipment is decreasing.

Review of facility-level activity data

In all instances where site-specific activity data are obtained through surveys, inventory agencies should compare the activity data between sites (adjusting for relative size or capacity) to identify significant outliers. They should investigate any outliers to determine if the differences can be explained or if there is an error in the reported activity.

Inventory agencies should compare national SF_6 production, adjusted for imports and exports, to the aggregated national SF_6 activity data for this source. This total national usage can be considered an upper bound on SF_6 emissions.

Verification of emissions estimates

For large countries, it may be possible to conduct an independent cross-check of national total SF_6 emissions estimates with top-down estimates derived from local atmospheric concentration measurements, provided that the inverse model calculation of emissions can be done with reasonable precision.

Inventory agencies should compare effective emission factors (loss rates) with values reported by other countries in the region, or with defaults published in the scientific literature that are calibrated to global total atmospheric concentrations. Transparent reporting, as outlined above, is essential for making international comparisons.

3.5.2 Other sources of SF_6

The *IPCC Guidelines* (Vol. 3, Section 2.17.4.7, Estimation of Emissions of HFCs and PFCs from Other Applications) describe other uses of SF_6 that lead to emissions. This source category excludes the following source categories that are reported elsewhere:

- Production and use in electrical equipment;
- Magnesium and aluminium production;
- Semiconductor manufacturing;
- Substituting in applications of Ozone Depleting Substances such as CFCs and halons (e.g. aerosol, fire extinguishing).

Identified remaining applications in this source category include:

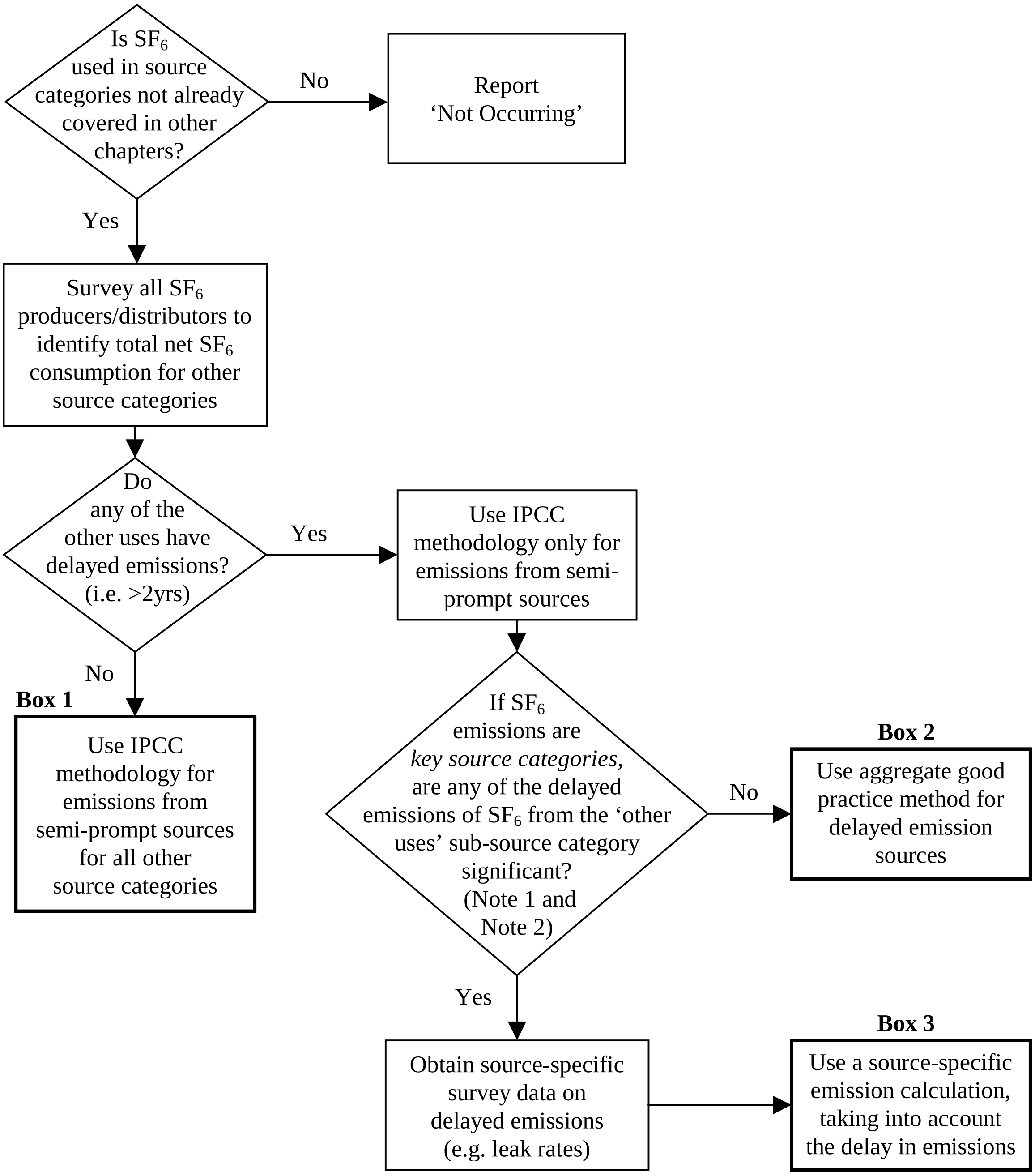
- Gas-air tracer in research and leak detectors;
- Medical purposes;
- Equipment used in accelerators, lasers and night vision goggles;
- Military applications;
- Sound-proof windows;
- Applications utilising its adiabatic property, e.g. car tires and sport attributes like tennis balls or shoe soles (i.e. using its low permeability through rubber).

3.5.2.1 Methodological issues

CHOICE OF METHOD

The *good practice* method is to use top-down import, export and consumption data from national SF_6 producers and distributors, disaggregated by major type of SF_6 application (see Figure 3.8, Decision Tree for Other Uses of SF_6). Acquiring this data will entail a survey of all SF_6 producers and distributors to identify total net SF_6 consumption. Once the data are obtained, the amount of SF_6 consumed by application in this source category should be estimated.

Figure 3.8 Decision Tree for Other Uses of SF_6



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Note 2: As a rule of thumb, a sub-source category would be significant if it accounts for 25-30% of emissions from the source category.

In many of the miscellaneous applications identified above, SF_6 is emitted within two years of consumption (e.g. tracers and in medical applications). *Good practice* in calculating SF_6 emissions from these 'semi-prompt' emissive applications is to use the following formula, as outlined in the *IPCC Guidelines*:

EQUATION 3.22

$$\text{Emissions in year t} = (0.5 \bullet \text{Amount Sold in year t}) + (0.5 \bullet \text{Amount Sold in year t} - 1)$$

This equation is similar to the equation for halocarbon emissions where an average delay of one year is assumed.

If, as a result of an initial survey, applications with distinctive delayed emissions appear significant, then *good practice* is to use a source category-specific emission calculation, taking into account the delay in emissions. For two delayed emission applications the following formulas can be used (based on experience in Germany):

- *Adiabatic property applications*: For car tires, a delay in emissions of 3 years is assumed (Schwarz *et al.*, 1996). For other applications such as shoes and tennis balls, the same delay time may be used:

EQUATION 3.23

$$\text{Emissions in year } t = \text{Sales in year } t - 3$$

- *Double-glazed soundproof windows*: Approximately 33% of the total amount of SF_6 purchased is released during assembly (i.e. filling of the double glass window). Of the remaining stock contained inside the window, an annual leakage rate of 1% is assumed (including glass breakage). Thus, about 78% of initial stock is left at the end of its 25-year lifetime. The application of SF_6 in windows began in 1975, so disposal is only beginning to occur. Emissions from this source sub-category should be calculated using Equations 3.24 to 3.26:

EQUATION 3.24

$$\text{Assembly Emissions} = 0.33 \bullet \text{Window Capacity}$$

EQUATION 3.25

$$\text{Leakage Emissions in year } t = 0.01 \bullet \text{Existing Stock in the Window}$$

EQUATION 3.26

$$\text{Disposal Emissions} = \text{Amount Left in Window at End of Lifetime} \bullet (1 - \text{Recovery Factor})$$

Unless country-specific data are available, a default recovery factor value of zero should be assumed in Equation 3.26. Use in military applications and for particle accelerators could also lead to delayed emissions. If no specific information is available for these sub-source categories, *good practice* is to treat them as semi-prompt emissions.

CHOICE OF EMISSION FACTORS

The emission factors required for these estimates can be found in the *IPCC Guidelines.* If inventory agencies use regional or country-specific data, it is *good practice* to clearly document them.

CHOICE OF ACTIVITY DATA

The activity data for these sub-source categories should be consistent with the data used in the calculation of SF_6 emissions from other source categories (e.g. electrical equipment) to ensure that the estimate is complete and there is no double counting.

COMPLETENESS

Data per application on import, export and consumption from national SF_6 producers and distributors will suffice, provided that (i) all SF_6 producers and distributors are identified, (ii) domestic consumers only purchase SF_6 from national suppliers, and (iii) imports and exports in products (e.g. sport attributes) are negligible. It is *good practice* to check regularly for additional distributors to ensure that no SF_6 is imported directly (in bulk) by end-users and that identified products containing SF_6 are not imported in sizeable amounts.

DEVELOPING A CONSISTENT TIME SERIES

For base year estimates, data may be needed for a few years prior to the base year; one year for semi-prompt emissions and more years for delayed emission applications. It is *good practice* to calculate emissions of SF_6 using the same method for every year in the time series. Where data are unavailable to support a more rigorous method for all years in the time series, it is *good practice* to recalculate according to the guidance provided in Chapter 7, Methodological Choice and Recalculation, Section 7 3.2.2, Alternative Recalculation Techniques.

UNCERTAINTY ASSESSMENT

If the survey of domestic sales per application by national SF_6 producers and distributors is complete, then the accuracy of annual apparent consumption data will be high. The uncertainty in emissions estimates will be similarly small when the uses are all semi-prompt emissions. In case of delayed emission applications the uncertainties are:

- Default delay times in adiabatic property applications: 3±1 year;
- Defaults for soundproof windows: 50±10% filling emissions and 1±0.5% leakage/breach emissions.

3.5.2.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving. It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced.

For transparency, it is *good practice* to report both actual and potential emissions from the source category ‘other uses’ separately from other SF_6 emissions. In addition, providing information on the specific applications that are included in this source category is useful for comparing (estimates of) national practices with other countries, regionally, or globally. In addition, the methods applied and references should be documented. For delayed emission sub-source categories, annual emissions, delay times and emission factors per type of sub-source category should be reported.

3.5.2.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

Additional procedures specific to other sources of SF_6 are outlined below:

Comparison of emissions estimates using different approaches

Inventory agencies should compare total national potential SF_6 emissions (minus the amount allocated to the electrical equipment use category, the semiconductor manufacturing use category, the metal production category and the SF_6 production category) to the estimated SF_6 emissions from other uses. The potential national emissions can be used as an upper bound on emissions.

Activity data check

Inventory agencies should compare the activity data submitted by different producers and distributors, and, adjusting for relative size or capacity of the companies, to identify significant outliers. Any outliers should be investigated to determine if the differences can be explained or if there is an error in the reported activity.

Comparison of emissions with other countries

Inventory agencies should compare the emissions from other SF_6 end-uses included in the national inventory with information submitted by other similar countries. For each source, emissions per capita or per unit of GDP with other countries should be compared. If national figures appear to be relatively very high or very small, a justification should be provided.

3.5.3 Production of SF_6

3.5.3.1 Methodological issues

The *IPCC Guidelines* do not provide a default emission factor for inadvertent losses during production and handling of SF_6. Although these emissions are likely to be small, emissions may be significant in some countries. For example, experience in Japan indicates an emission factor of 8% of the gas produced, including handling losses during disposal of residual gas in returned cylinders (Suizu, 1999). This is because there is a large demand for highly purified SF_6 gas, and impure gas may be released.

CHOICE OF METHOD

It is *good practice* to choose the method according to the decision tree in Figure 3.9, Decision Tree for SF_6 Production. The number of major SF_6 producers is quite small: globally about 6 companies produce SF_6 with about 10 production facilities world-wide (Preisegger, 1999). The number of smaller producers may grow in the near future, particularly in the Economies in Transition and in China. However, a survey of national producers should not be difficult to compile. These producers should provide an estimate of their total emissions.

Emissions of SF_6 may occur during production as well as handling of new gas at the site. Based on German experience, a default emission factor of 0.2% of the total quantity of SF_6 produced is suggested for those countries in which the predominant end use does not require highly purified SF_6 gas (e.g. electrical equipment, insulated windows) (Preisegger, 1999). As discussed above, in countries where the major uses require highly purified SF_6 gas (e.g. semiconductor manufacturing), the default value should be 8%. If national data are available, these should be used.

Recycling of used gas may be done by the producers of new gas or by other recycling firms. Emissions may occur during handling and purification of old gas and handling of recycled gas. Specific emission factors are not available. Thus, *good practice* is to use the default factor for new production (0.2%).

UNCERTAINTY ASSESSMENT

Production emissions can be negligible (e.g. when scrubbers capture the SF_6 gas released). The estimated uncertainty range for the default emission factor is therefore 0.2±0.2 (%). Relative uncertainty of the default 8% emission factor is of the same order.

COMPLETENESS

For some inventory agencies, identifying smaller producers and, in particular, recycling firms may be a difficult task. However, initial estimates based on the national mass balance of SF_6 should identify if such entities provide a sizeable contribution to total national emissions.

3.5.3.2 Reporting and documentation

Confidentiality issues may arise where there are limited numbers of manufacturers. In these cases more aggregate reporting of total national SF_6 applications may be necessary. If survey responses cannot be released as public information, third-party review of survey data may be necessary to support data verification efforts.

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving. It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced.

3.5.3.3 Inventory quality assurance/quality control (QA/QC)

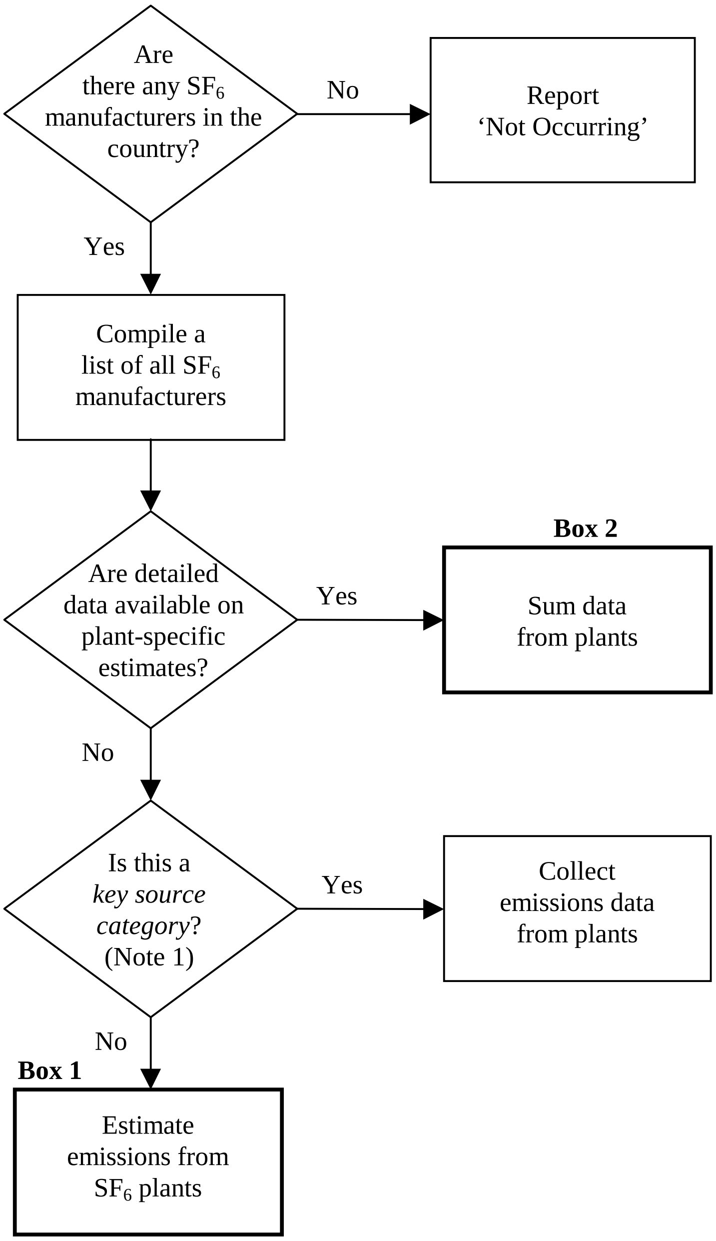
It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category.

Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

Comparison of emissions estimates using different approaches

Inventory agencies should compare the estimate based on aggregated producer-level data to an estimate based on national production data and the suggested default emission factor of 0.2%. They should investigate significant discrepancies in cooperation with the producers to determine if there are unexplained differences.

Figure 3.9 Decision Tree for SF_6 Production



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

3.6 PFC, HFC, SF_6 EMISSIONS FROM SEMICONDUCTOR MANUFACTURING

3.6.1 Methodological issues

The semiconductor industry currently emits fluorocarbons (CF_4, C_2F_6, C_3F_8, c-C_4F_8, CHF_3), nitrogen trifluoride (NF_3), and sulfur hexafluoride (SF_6) from its manufacturing process.[30] These gases, collectively referred to as fluorinated compounds (FCs), are used in two important steps of semiconductor manufacturing: (i) plasma etching thin films and (ii) cleaning chemical vapour deposition (CVD) tool chambers. In addition, a fraction of the fluorocarbons used in the production process are converted into CF_4.

CHOICE OF METHOD

Emissions vary according to the gases used in manufacturing different types of semiconductors, the process (or more roughly, process type (CVD or etch)) used, the brand of process tool used, and the implementation of atmospheric emission reduction technology.

The *IPCC Guidelines* do not provide specific guidance on how to estimate greenhouse gas emissions from semiconductor manufacturing. However, using the basic methodological principles outlined in the *IPCC Guidelines* for other source categories, four alternative methods for estimating FC emissions are described below. The use of the 'Tier' terminology in this section corresponds to increasing data requirements and sophistication of the emission estimation process. The choice of methods will depend on data availability and is outlined in the decision tree, see Figure 3.10, Decision Tree for FC Emissions from Semiconductor Manufacturing.

Continuous emissions monitoring is currently viewed as neither a technically nor economically viable means to estimate emissions from this industry. Thus, all four methods are based on gas sales/purchases data and a series of parameters that affect emissions. The most rigorous method, Tier 2a method, requires company-specific values for the parameters rather than defaults. The Tier 2b method uses company-specific data on the share of gas used in *etching* versus *cleaning* and the share of gas used in processes with emission control technology, but relies on default values for some or all of the other parameters. The Tier 2c method uses company-specific data on the share of gas used in processes with emission control technology, but does not distinguish between etching and cleaning, and uses default values for the other parameters. The Tier 1 method uses default values for all parameters and does not account for the use of emission control technology.

Tier 2a Method – Process-specific parameters

This method is appropriate where company-specific or plant-specific values are available for the following parameters: the amount of gas fed into each process or tool (or into small subsets of processes or tools), the fraction of purchased gas remaining in the shipping container after use (heel), the fraction of the gas 'used' (destroyed or transformed) in the semiconductor manufacturing process, the fraction of the gas converted to CF_4 during semiconductor manufacture, the fraction of the gas fed into processes with emission control technologies, and the fraction of the gas destroyed by those emission control technologies. For purposes of transparency and comparability, the values used for these emission parameters should be well documented (see Choice of Emission Factors).

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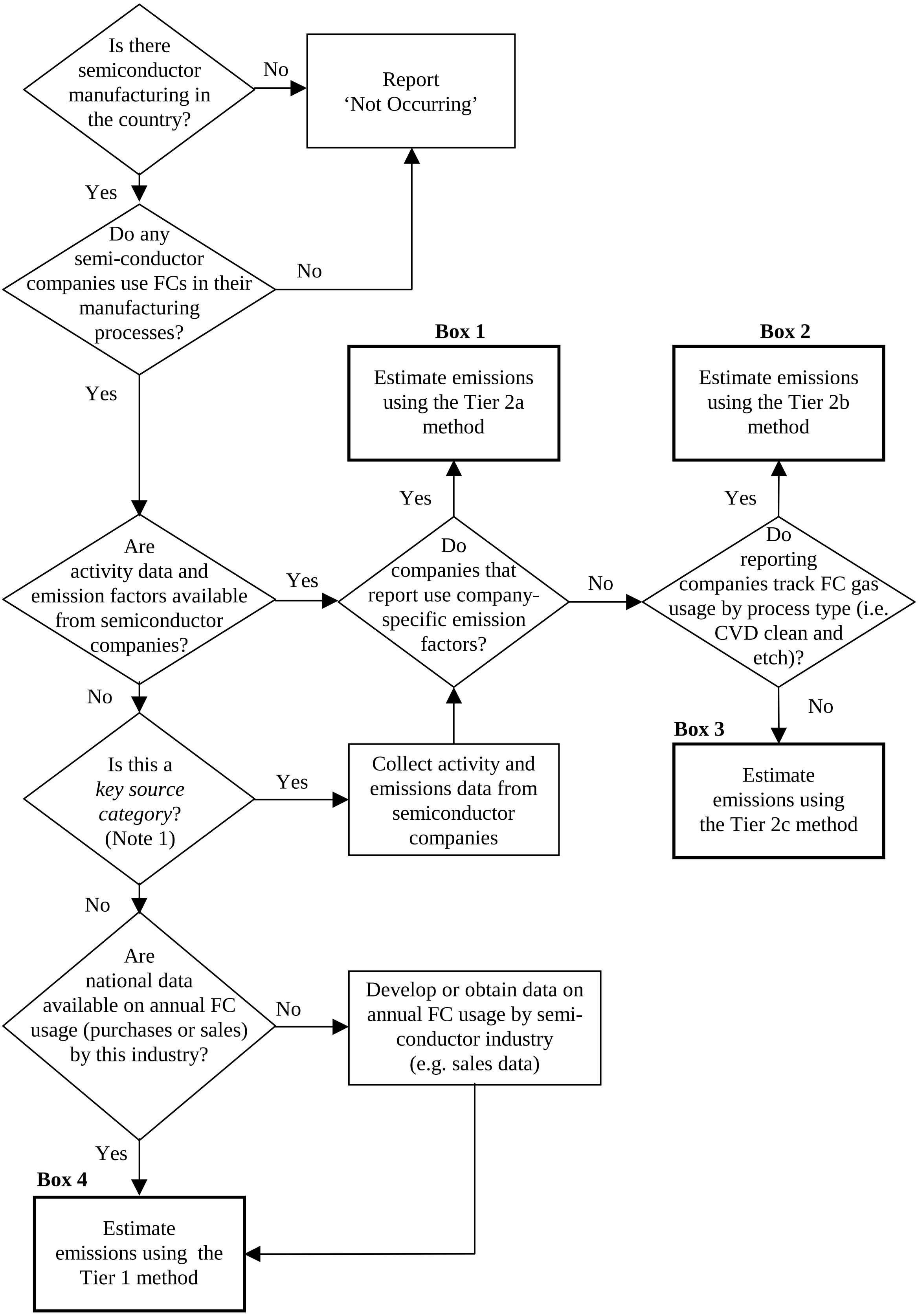
[30] Although NF_3 does not currently have a global warming potential (GWP) recognized by the IPCC, NF_3 emissions are discussed in this chapter. Molina *et al.* have estimated a GWP-100 of 8,000 and an atmospheric lifetime of 740 years (Molina, 1995).

Figure 3.10 Decision Tree for FC Emissions from Semiconductor Manufacturing



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Emissions resulting from the use of a specific FC (FC_i) consist of emissions of FC_i itself *plus* emissions of CF_4 created as a by-product during the use of FC_i . The following calculation should be repeated for each gas for each process type:

EQUATION 3.27

$$\text{Emissions of } FC_i = (1 - h) \bullet \sum_p [FC_{i,p} \bullet (1 - C_{i,p}) \bullet (1 - a_{i,p} \bullet d_{i,p})]$$

Where:

p = Process or process type (etching or CVD chamber cleaning)

$FC_{i,p}$ = kg of gas i fed into process/process type p (CF_4, C_2F_6, C_3F_8, C_4F_8, CHF_3, NF_3, SF_6)

h = Fraction of gas remaining in shipping container (heel) after use

$C_{i,p}$ = Use rate (fraction destroyed or transformed) for each gas i and process/process type p (in kgs)

$a_{i,p}$ = Fraction of gas volume fed into in processes with emission control technologies (company-or plant-specific)

$d_{i,p}$ = Fraction of gas i destroyed by the emission control technology (If more than one emission control technology is used in process/process type p, this is the average of the fraction destroyed by those emission control technologies, where each fraction is weighted by the quantity of gas fed into tools using that technology)

EQUATION 3.28

$$\text{By-product Emissions of } CF_4 \text{ for } FC_{i,p} = (1 - h) \bullet \sum_p [B_{i,p} \bullet FC_{i,p} \bullet (1 - a_{i,p} \bullet d_{CF4,p})]$$

Where:

$B_{i,p}$ = Fraction of gas i transformed into CF_4 for each process/process type

$d_{CF4,p}$ = Fraction of CF_4 by-product destroyed by the emission control technology (e.g. control technology type listed in Table 3.15, Default Emission Factors for HFC, PFC, and SF_6 Emissions from Semiconductor Manufacturing)

After estimating CF_4 emissions for each gas, inventory agencies or companies should sum these emissions across all gases to arrive at an estimate of aggregate CF_4 emissions.

Tier 2b Method – Process type-specific parameters

The Tier 2b method also uses the Equations 3.27 and 3.28. However, instead of distinguishing among processes or small sets of processes, it distinguishes only between process types (etching vs. CVD chamber cleaning). Consequently, the Tier 2b method requires data on the aggregate quantities of each gas fed into all etching processes and all cleaning processes ($FC_{i,p}$), as opposed to the quantities of each gas fed into each individual process. Industry-wide generic default values are used for any or all of the following: the fraction of the gas remaining in the shipping container (h), the fraction of the gas 'used' (destroyed or transformed) per process type ($C_{i,p}$), and the fraction of the gas converted into CF_4 in the process type (B_i). Defaults are also presented for the fraction of the gas destroyed by the emissions control technology ($d_{i,p}$ and $d_{CF4,p}$). Company or plant-specific emission factors may be substituted for default values when available. The equations account for the plant-specific use of emission-control devices, but do not account for differences among individual processes or tools or among manufacturing plants in their mix of processes and tools. Thus, Tier 2b estimates will be less accurate than Tier 2a estimates.

Tier 2c Method – FC-specific parameters

This method calculates emissions for each FC used on the basis of company-specific data on gas sales or purchases and on emission control technologies. It uses industry-wide generic default values for the fraction of the purchased gas remaining in the shipping container after use (h), the fraction of the gas 'used' (destroyed or transformed) in the semiconductor manufacturing process, and the fraction of the gas converted into CF_4 in semiconductor manufacture. As is the case with the Tier 2a and 2b methods, total emissions are equal to the sum of emissions from the gas FC_i used in the production process plus the emissions of by-product CF_4 resulting from use of the gas FC_i., as shown in Equations 3.29 and 3.30. Unlike Tier the 2a and 2b methods, the Tier 2c method does not distinguish between processes or process types.

As discussed below in the section on emission factors, the Tier 2c method uses the emission factor for the process type (CVD or etch) in which the individual FC is most frequently used in the semiconductor industry. This method reflects a current trend where individual FCs tend to be used predominantly in particular process types (CVD or etch) throughout the semiconductor industry. However, in countries with companies or plants that depart significantly from the industry-wide pattern of usage (e.g. by using a gas primarily in etch while others primarily use it in CVD), inventory agencies should evaluate the potential to introduce error by using the Tier 2c method rather than the Tier 2b method.

EQUATION 3.29

$$\text{Emissions of } FC_i = (1 - h) \bullet [FC_i \bullet (1 - C_i) \bullet (1 - a_i \bullet d_i)]$$

Where:

FC_i = Sales/purchases of gas i in kg (CF_4, C_2F_6, C_3F_8, c-C_4F_8, CHF_3, NF_3, SF_6)

h = Fraction of gas remaining in shipping container (heel) after use

C_i = Use rate of gas (fraction destroyed or transformed in process)

a_i = Fraction of gas i volume used in processes with emission control technologies (company- or plant-specific)

d_i = Fraction of gas i destroyed by the emission control technology

EQUATION 3.30

$$\text{By-product Emissions of } CF_4 \text{ for } FC_i = (1 - h) \bullet [(B_i \bullet FC_i) \bullet (1 - a_i \bullet d_{CF_4})]$$

Where:

B_i = kg CF_4 created per kg of gas i used

d_{CF4} = Fraction of CF_4 by-product destroyed by the emission control technology

After estimating CF_4 emissions for each gas, inventory agencies or companies should sum these emissions across all gases to arrive at an estimate of aggregate CF_4 emissions.

This method does not account for differences among process types (etching versus cleaning), individual processes, or tools.

Tier 1 Method – Default

The Tier 1 method is the least accurate estimation method. It should be used only in cases where company-specific data are not available. This method calculates emissions for each FC used on the basis of national gas sales or purchase data. It uses industry-wide generic default values for: the fraction of the purchased gas remaining in the shipping container after use, the fraction of the gas 'used' (transformed or destroyed) in the semiconductor manufacturing process, and the fraction of the gas transformed into CF_4 in semiconductor manufacture. As is the case with the Tier 2 method, emissions are equal to the sum of emissions from the gas FC_i used in the production process plus the emissions of by-product emissions of CF_4 resulting from use of the gas $FC_{i.}$, as shown in Equations 3.31 and 3.32.

EQUATION 3.31

$$\text{Emissions of } FC_i = (1 - h) \bullet [FC_i \bullet (1 - C_i)]$$

Where:

FC_i = Sales/purchases of gas i in kg (CF_4, C_2F_6, C_3F_8, c-C_4F_8, CHF_3, NF_3, SF_6)

h = Fraction of gas remaining in shipping container (heel) after use

C_i = Use rate of gas (fraction destroyed or transformed in process)

EQUATION 3.32

$$\text{Emissions of } CF_4 \text{ for } FC_i = (1 - h) \bullet (B_i \bullet FC_i)$$

Where:

B_i = kg CF_4 created per kg of gas i

After estimating CF_4 emissions for each gas, inventory agencies or companies should sum them across all gases to arrive at an estimate of aggregate CF_4 emissions.

This method does not account for differences among process types (etching versus cleaning), individual processes, or tools. It also does not account for the possible use of atmospheric emission-control devices.

CHOICE OF EMISSION FACTORS

As discussed above, emissions factors based on simple semiconductor production variables are not adequate to account for all of the factors that influence emissions. Data for each of the following parameters are necessary to prepare a rigorous estimate:

- The gases used;
- The process type (CVD or etch) used;
- The brand of process tool used;
- Atmospheric emission reduction technology.

Default values have been developed for the parameters used in Tier 1, Tier 2b and 2c methods that reflect the literature and expert judgement (see Table 3.15, Default Emission Factors for HFC, PFC and SF_6 Emissions from Semiconductor Manufacturing). Given the difficulty in representing the diverse production conditions within the semiconductor industry, default emission parameters are inherently uncertain. Accuracy can be improved with larger sets of measured data and where factors are applied to similar processes using similar or identical chemical recipes. Emission factors for destruction (abatement) technologies are acknowledged as currently having greater uncertainty and variability than those for the manufacturing processes. Rapid technical innovation by chemical and equipment suppliers, and semiconductor manufacturers is expected to result in major emission reductions within this industry over the next 10 years. These innovations are also likely to affect emission factors. The semiconductor industry has established a mechanism through the World Semiconductor Council to evaluate global emission factors. Inventory agencies may wish to periodically consult with the industry to better understand global and national circumstances.

The default value for the fraction of gas remaining in the shipping container (heel) is 0.10.

TABLE 3.15
DEFAULT EMISSION FACTORS FOR HFC, PFC AND SF_6 EMISSIONS FROM SEMICONDUCTOR MANUFACTURING

	CF_4	C_2F_6	CHF_3	C_3F_8	$c\text{-}C_4F_8$	NF_3	SF_6
Tier 1							
$1 - C_i$	0.8	0.7	0.3	0.4	0.3	0.2	0.5
B	NA	0.1	NA	0.2	NA	NA	NA
Tier 2c							
$1 - C_i$	0.8	0.7	0.3	0.4	0.3	0.2	0.5
B	NA	0.1	NA	0.2	NA	NA	NA
Tier 2b							
Etch $1 - C_i$	0.7	0.4	0.3	0.4	0.3	0.3[a]	0.5
CVD $1 - C_i$	0.8	0.7	NA	0.4	ND	0.2	0.2
Etch B	NA	0.1	NA	ND	NA	NA	NA
CVD B	NA	0.1	NA	0.2	NA	NA	NA
Emission Control Technology (d)	**CF_4**	**C_2F_6**	**CHF_3**	**C_3F_8**	**$c\text{-}C_4F_8$**	**NF_3**	**SF_6**
Tier 2c[b]	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Tier 2b							
Hot Tube[c]	0.1	0.3	NT	NT	NT	0.5	0.1
Fueled combustion[d]	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Plasma (with additive H_20 vapour)[e]	0.9	NT	0.9	NT	0.9	0.9	0.9
Plasma (with additive O_2)	0.9	NT	0.9	NT	0.9	0.8	0.8
Catalytic[f]	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Cryogenic absorption	0.7	0.9	0.9	NT	NT	NT	0.9
Membrane Separation	0.8	0.9	NT	NT	NT	NT	0.9

[a] Use of NF_3 in the etch process is typically small compared to CVD. The aggregate emissions of NF_3 from etch and CVD under Tier 2b will usually not be greater than estimates made with Tier 2c or Tier 1 methods.

[b] Tier 2c emission control technology factors are applicable only to fueled combustion, plasma, and catalytic devices that are specifically designed to abate FCs. Under the Tier 2c approach, other technologies, such as hot tubes, are assumed to have a destruction efficiency of 0%.

Sources:

[c] SEMATECH Technology Transfer Report, SEMATECH, 1994.

[d] Vendor data verified by semiconductor manufacturers.

[e] Draft SEMATECH Technology Transfer Report, SEMATECH, 1999.

[f] Data for catalytic, cryogenic absorption and membrane separation as presented at *Semicon SW 1999*, Austin, Texas, USA.

NA = not applicable, ND = no data, NT = not tested.

PROCESS TOOL EMISSION FACTORS

The procedures for calculating process tool emission factors for Tier 1, Tier 2c and Tier 2b methods are identical. Process tool emission factors are defined as the amount of greenhouse gas emitted divided by the amount of greenhouse gas used in the process. The emission factors correspond to the ‘$(1 – C_i)$’ term in the Tier 1 and Tier 2 formulas. For example, the emission factor of 0.8 for CF_4 (see Table 3.15 above, Tier 1 value) means that 80% of the CF_4 used in the process is emitted as CF_4. By-product emission factors were also calculated. The expert group determined that the only by-product emission of significance was that of CF_4. It was further determined that the only gases that emit significant amounts of CF_4 as a by-product are C_2F_6 and C_3F_8. As a result of this discussion, CF_4 by-product emission factors were calculated only for C_2F_6 and C_3F_8. For example, a value of 0.2 for C_3F_8 (taken from Table 3.15 above, Tier 1 value) means that 20% of the C_3F_8 used is converted into CF_4.

In order to calculate the Tier 2b process tool emission factors, data were collected from the process equipment manufacturers and semiconductor manufacturers. The data were collected according to process type (either Chemical Vapor Deposition (CVD) or etch) and also by type of gas (e.g. C_2F_6, CF_4). The methods used to conduct the emissions testing were real time Quadrupole Mass Spectrometry (QMS) and Fourier Transform Infrared Spectroscopy (FTIR). Calibration standards (usually 1% mixtures with a balance of N_2) were used to quantify the results. The quality analysis and quality control requirements that were followed are outlined in the ‘Equipment Environmental Characterisation Guidelines’ Revision 3. The emission factors for Tier 2b (see Table 3.15 above) are the simple average of the data collected for each gas for etch and CVD, rounded to one significant figure.

In order to determine the Tier 1 and Tier 2c process tool emission factors, some knowledge of the amounts of gas used in typical semiconductor manufacturing processes is required. The Tier 1 and Tier 2c emission factors were obtained by determining for each of the gases which process type (CVD or etch) uses the most gas. For example, the Tier 2b emission factors for SF_6 are 0.5 (etch) and 0.2 (CVD). Since the predominant use of SF_6 in the semiconductor industry is in the etch processes, the Tier 2b etch emission factor was used for the Tier 1 SF_6 emission factor.

For Tier 2a emission factors, semiconductor manufacturers use company or fab-specific values rather than using default values as listed in Table 3.15 above.[31] In order to assure the quality of emission factors, emission testing should be conducted in accordance with accredited methods.[32] If a third-party supplier conducts the emissions testing, the semiconductor manufacturer should make sure that the third-party supplier is capable of meeting all of the requirements outlined in Revision 3.0 of the Equipment Environmental Characterisation Guidelines. Semiconductor manufacturers who use emission factors provided by the process tool equipment supplier should make sure that the emission factors are applicable to their specific manufacturing process. Manufacturing methods with process parameters (e.g. pressure, flow rate) that deviate from centreline conditions may have different emission factors than those provided by the tool manufacturer.[33]

EMISSION CONTROL TECHNOLOGY FACTORS

Tier 2b Emission Factors

Assumptions for the emissions control technology emission factors for the Tier 2b methods include:

(i) Results listed are for actual fab emissions testing, no lab results were included;

(ii) Plasma abatement is applicable to etch tools only (less than or equal to 200mm);

(iii) Capture/Recovery (cryogenic absorption and membrane separation) emission factors are for the capture portion of process only, recovery efficacy must be further characterised;

(iv) Cost of ownership and applicability of various technologies vary widely;

(v) Applicability of various technologies to emission from >200 mm wafer processes was not characterised.

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[31] ‘Fab-specific’ means specific to a fabrication plant.

[32] One example of an internationally accredited testing method can be found in the latest version of the Semiconductor Industry Association (2000) ‘Equipment Environmental Characterisation Guidelines’ (Revision 3.0 as of February 2000)’.

[33] Centreline conditions refer to the conditions under which equipment manufacturers standardise their equipment for sale. It is common for semiconductor manufacturers to modify these conditions to optimise for particular needs.

The values presented in Table 3.15, Default Emission Factors for HFC, PFC and SF_6 Emissions from Semiconductor Manufacturing, are the average of all of the data received for each type of technology and input gas, rounded down to the next 10% (e.g. an average of 98% would be rounded down to 0.9). The averages were rounded down to reflect that (i) emissions control devices vary in their efficacy depending upon what gas they are optimised to destroy, and (ii) the efficacy of emission control devices on new tools processing larger wafers (>200 mm) is not well characterised. An emission control device that can destroy 99% of a FC when it is optimised to destroy that FC on a certain tool may destroy less than 95% of that FC when it is optimised to destroy something else or when it is used on a tool for which it was not designed.

Emissions control technologies, while currently not widely deployed in the industry, are developing at a rapid pace. Default control technology emission factors in Table 3.15, Default Emission Factors for HFC, PFC and SF_6 Emissions from Semiconductor Manufacturing, are based on limited testing of control devices in a small subset of processes and tools. Results are expected to vary across tools and gas flow rates. In addition, individual abatement technologies are not applicable to all tools or processes in semiconductor manufacturing facilities.

Tier 2c Emission Factors

The emission control technology factors listed for Tier 2c were calculated from data received from equipment suppliers, abatement suppliers and semiconductor manufacturers. Again, the values are the average of all of the data received for each type of input gas, rounded down to the next 10% It should be noted that only data from abatement devices that were specifically designed to abate FCs were used in the average calculation. Data were received from combustion abatement devices (all of which used some type of fuel), plasma abatement devices, and catalytic abatement devices. Default control technology emission factors for Tier 2c should be used only for emissions control technologies specifically designed and installed to reduce FC emissions. If companies use any other type of abatement device, such as a hot tube, they should assume that its destruction efficiency is 0% under the Tier 2c method. Emissions control technologies are expected to evolve over time and emission factors should be re-evaluated periodically.

CHOICE OF ACTIVITY DATA

Activity data for this industry consists of data on gas sales, purchases, or use. For the more data-intensive Tier 2 methods, gas purchase data at the company or plant-level are necessary. For the Tier 1 method, it is preferable that company-level gas purchase data are used. Where purchase data are not available, sales data may be available from the gas manufacturers or distributors. Sales data should include only the share of each gas that is sold to the semiconductor industry. It may be necessary to make assumptions about this share if the data are not available from gas manufacturers or distributors.

UNCERTAINTY ASSESSMENT

Use of the Tier 2a method will result in the least uncertain inventory and the Tier 1 method is the most uncertain. Given the limited number of plants and the close monitoring of production processes at the plant level, collection of data for use in Tier 2b or Tier 2a methods should be technically feasible. The Tier 1 method has the greatest level of uncertainty. Inventory agencies should seek the advice of the industry on uncertainties, using the approaches to obtaining expert judgement outlined in Chapter 6, Quantifying Uncertainties in Practice.

COMPLETENESS

Complete accounting of emissions from the semiconductor industry should be achievable in most countries because there are a limited number of companies and plants. There are four issues related to completeness that should be addressed:

- **Other by-products:** A number of transformation by-products are generated as a result of FC use for chamber cleaning and etching. With the exception of CF_4, however, FC by-product concentrations are assumed to be negligible. Inventory agencies should re-evaluate this assumption if new gases are adopted by the industry.

- **New chemicals:** Completeness will be an issue in the future as the industry evaluates and adopts new chemical processes to improve its products. Industry-wide efforts to reduce FC emissions are also accelerating the review of new chemicals. Consequently, *good practice* for this industry is to incorporate a mechanism that accounts for greenhouse gases not listed in the IPCC Second Assessment Report (e.g. NF_3, C_5F_8, HFEs). These new gases may also produce high GWP by-products.

- **Other sources:** A small amount of FCs may be released during gas handling (e.g. distribution) and by sources such as research and development (e.g. university) scale plants and tool suppliers. These emissions are not believed to be significant (e.g. less than 1% of this industry's total emissions).
- **Other products or processes:** FC use has been identified in the electronics industry in emissive applications including: manufacture of flat panel displays[34] and hard disk drives reliability testing (inert liquids), coolants[35] (direct evaporative cooling for electric and electronic apparatuses and indirect coolants in closed circuit of electric and electronic apparatuses), vapour phase reflow soldering, and precision cleaning.[36]

DEVELOPING A CONSISTENT TIME SERIES

Use of FCs by the semiconductor industry began in the late 1970s and accelerated significantly beginning in the early 1990s. Determining a base year emissions level may present difficulties because few data are available for emissions occurring before 1995. If historical emissions estimates were based on simple assumptions (e.g. use equals emissions), then these estimates could be improved by applying the methods described above. If historical data are not available to permit use of a Tier 2 method, then the Tier 1 method using default emission parameters can be used retrospectively. Both Tier 1 and Tier 2 could then be applied simultaneously for the years in which more data become available to provide a comparison or benchmark. This should be done according to the guidance provided in Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques.

In order to ensure a consistent emissions record over time, an inventory agency should recalculate FC emissions for all years reported whenever emissions calculation procedures are changed (e.g. if an inventory agency changes from the use of default values to actual values determined at the plant level). If plant-specific data are not available for all years in the time series, the inventory agency will need to consider how current plant data can be used to recalculate emissions for these years. It may be possible to apply current plant-specific emission parameters to sales data from previous years, provided that plant operations have not changed substantially. Such a recalculation is required to ensure that any changes in emission trends are real and not an artefact of changes in procedure.

3.6.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving. It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced.

Explicit reporting on emissions in this industry would improve the transparency and comparability of emissions. For example, under Table 2F of the IPCC reporting tables an additional line should be added for semiconductor manufacturing emissions. As a number of FCs gases are emitted by this industry, reporting by individual gas species rather than by chemical type would also improve the transparency and usefulness of this data. Efforts to increase transparency should take into account the protection of confidential business information related to specific gas use. Country-level aggregation of gas-specific emissions data should protect this information in countries with three or more manufacturers. Table 3.16, Information Necessary for Full Transparency of Estimates of Emissions from Semiconductor Manufacturing, shows the supporting information necessary for full transparency in reported emissions estimates.

Good practice for Tier 2a is to document the development of company-specific emission factors, and to explain the deviation from the generic default values. Given confidentiality concerns, inventory agencies may wish to aggregate this information across manufacturers. In cases where manufacturers in a country have reported

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[34] Emissions from flat panel display (thin film transistor (TFT) liquid crystal) manufacturing may be estimated using methods similar to those used for semiconductor manufacturing. Company-specific emission and abatement factors are required. Very small amounts are also used in microelectronic machine (MEM) manufacturing and research and development laboratories/facilities.

[35] Emissions from 'hard disc drives reliability testing' and 'coolants' are to be accounted for in Section 3.7.6, Other Applications Sub-source Category.

[36] Emissions from precision cleaning are to be accounted for in Section 3.7.2, Solvents Sub-source Category.

different emission or conversion factors for a given FC and process or process type, inventory agencies may provide the range of factors reported and used.

Until handling of NF_3, C_5F_8, HFEs, and other FC gases is decided upon, emissions should be reported separately and not included in total emissions calculations.

TABLE 3.16
INFORMATION NECESSARY FOR FULL TRANSPARENCY OF ESTIMATES OF EMISSIONS FROM SEMICONDUCTOR MANUFACTURING

Data	Tier 1	Tier 2c	Tier 2b	Tier 2a
Emissions of each FC (rather than aggregated for all FCs)	X	X	X	X
Sales/purchases of each FC	X	X		
Mass of each FC used in each process or process type			X	X
Fraction of each FC used in processes with emission control technologies		X	X	X
Use rate for each FC for each process or process type (This and following information is necessary only if default value is not used)				X
Fraction of each FC transformed into CF_4 for each process or process type				X
Fraction of gas remaining in shipping container				X
Fraction of each FC destroyed by emission control technology				X
Fraction of CF_4 by-product destroyed by emission control technology				X

3.6.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

Additional general guidance for higher tier QA/QC procedures is also included in Chapter 8. Due to the highly competitive nature of the semiconductor industry, provisions for handling confidential business information should be incorporated into the verification process. Methods used should be documented, and a periodic audit of the measurement and calculation of data should be considered. A QA audit of the processes and procedures should also be considered.

3.7 EMISSIONS OF SUBSTITUTES FOR OZONE DEPLETING SUSBSTANCES (ODS SUBSTITUTES)

Overview (3.7.1 to 3.7.7)

This chapter provides *good practice guidance* on seven sources of emissions of substitutes for ozone depleting substances (ODS). Each of the following uses is discussed in a separate section:

- Aerosols and metered dose inhalers;
- Solvent uses;
- Foam;
- Stationary refrigeration;
- Mobile air conditioning;
- Fire protection;
- Other applications.

General methodological issues for all ODS substitutes sub-source categories

CHOICE OF METHOD

The *IPCC Guidelines* describe two tiers for estimating emissions from the use of ODS substitutes: the advanced or actual method (Tier 2), and the ‘basic’ or ‘potential’ method (Tier 1).[37] The actual method (Tier 2) accounts for the time lag between consumption and emissions of ODS substitutes, whereas the potential method assumes that emissions occur during the year in which the chemical is produced or sold into a particular end-use sector.

While the Tier 1 method requires less data, it may produce very inaccurate estimates over the short term because, for many long-lived sources such as refrigerators, chemicals are emitted over a period of several years. The greater the length of time over which the chemical is released, the greater the possible inaccuracy of the ‘potential’ method. If, as is the case in most countries, equipment sales are increasing each year, the total amount of chemical stored in end-use equipment must also be increasing. Therefore, the potential method is likely to overstate emissions

Good practice is to use the Tier 2 actual method for all sub-source categories within this source category. Consistency requires that inventory agencies make every attempt to apply actual methodologies across the whole spectrum of ODS substitute emission sources. If an inventory agency is unable to implement actual methods for all sub-source categories, it is *good practice* to calculate and report potential estimates for all sub-source categories to allow the summation of total emissions. *Actual and potential emissions estimates should not be summed together by the inventory agency.*

The generalised decision tree in Figure 3.11, Generalised Decision Tree for All Substitutes for Ozone Depleting Substances, describes *good practice* in choosing between Tier 2 and Tier 1 methods for each end-use in the seven sub-sections that follow. *Good practice* is to use the Tier 2 method for those sub-source categories that were identified as ‘*key sub-source categories*’ as discussed in Chapter 7, Methodological Choice and Recalculation. This determination is done at the level of the IPCC source category level (in this case ‘ODS Substitutes’) and not at the level of the IPCC sub-source category.

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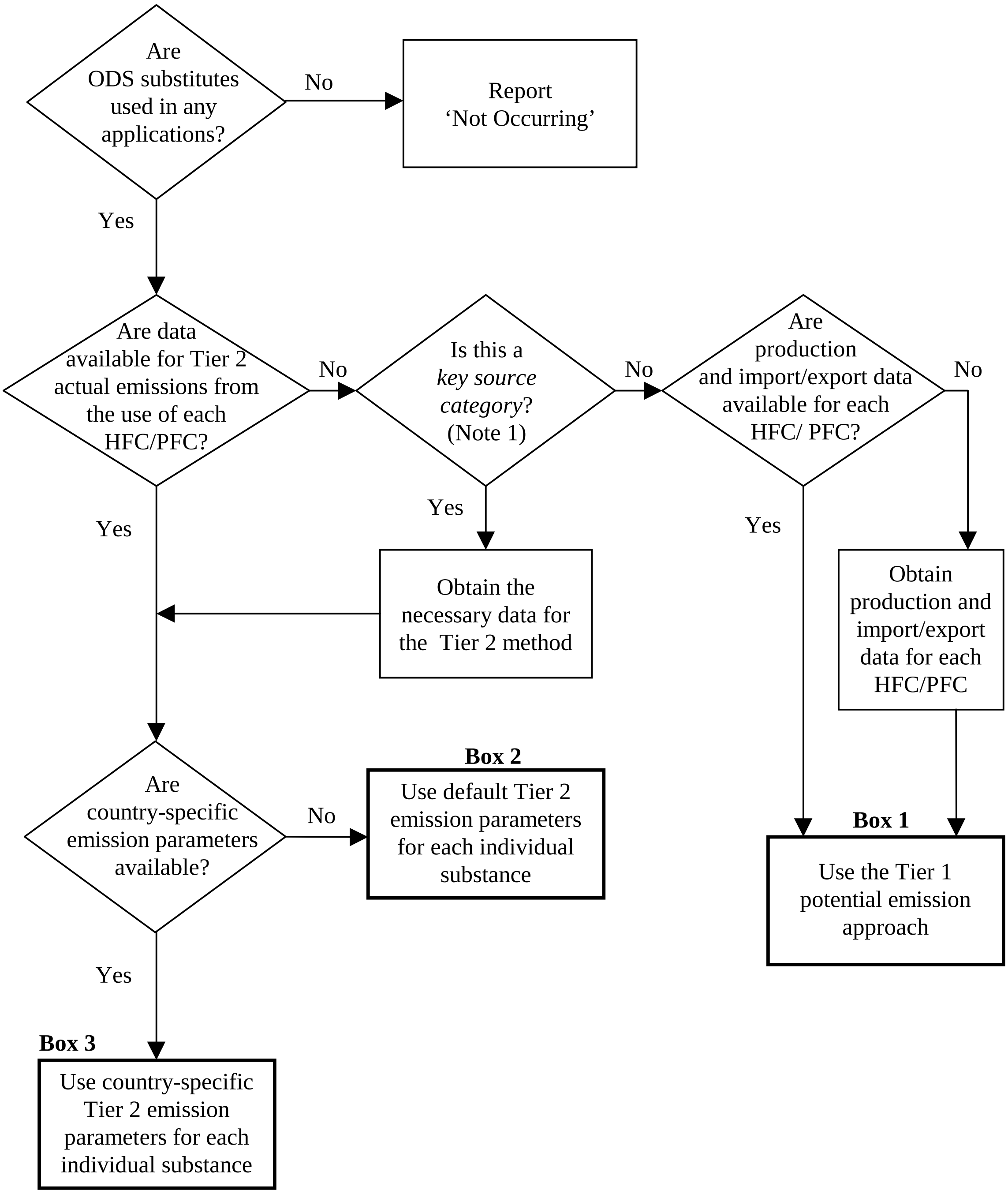
[37] The Conference of the Parties to the UNFCCC, at its third session, affirmed ‘… that the actual emissions of hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride should be estimated, where data are available, and used for the reporting of emissions. Parties should make every effort to develop the necessary sources of data;’. (Decision 2/CP.3, Methodological issues related to the Kyoto Protocol)

Figure 3.11 Generalised Decision Tree for All Substitutes for Ozone Depleting Substances



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

The *good practice guidance* in this section deals with variations of the Tier 2 method, rather than implementing the potential method. Each sub-section discusses how to apply these methods to specific ODS sub-source categories, reviews existing data sources, and identifies gaps therein. For further guidance on implementing the Tier 1 method, countries can refer to Section 2.17.3 of the *IPCC Guidelines*, Vol. 3.

In general, it is *good practice* to develop appropriate country data for the Tier 2 method when the emissions from the ODS replacement source categories are a significant component of the national inventory. This may require a country-specific model. More detailed decision trees are included for each sub-source category to assist in the further identification of data needs and selection of the Tier 2 approach.

Inventory agencies implementing the Tier 2 method will need to determine whether to use bottom-up or top-down approaches. The bottom-up approach takes into account the time lag between consumption and emissions explicitly through emission factors. The top-down approach takes the time lag into account implicitly, by tracking the amount of virgin chemical consumed in a given year that is used to replace chemical that was emitted to the atmosphere.

Tier 2a – Bottom-up approach

The bottom-up method is based on the number of products and end-uses where ODS substitutes are consumed and emitted. This approach estimates the number of equipment units that use these chemicals, average chemical charges, average service life, emission rates, recycling, disposal, and other pertinent parameters. Annual emissions are then estimated as a function of these parameters through the life of the units. Since equipment units vary significantly in the amount of chemical used, service life, and emission rates, the characterisation of this equipment can be a resource intensive task. The longer-lived the end-use equipment, and the more diverse the types of equipment within a particular application, the more complex the bottom-up approach has to be in order to account for emissions.[38] The bottom-up approach can provide an accurate estimate of emissions if the data called for by the following equation are available for all relevant types and vintages of equipment:

EQUATION 3.33

Total Emissions of Each PFC or HFC = Equipment Assembly Emissions + Equipment Operation Emissions + Equipment Disposal Emissions

Assembly emissions occur as fugitives when equipment is filled or refilled with a chemical. Emissions from equipment also occur as leaks, or intentional releases during *operation*. Finally, when the equipment life ends and it is *disposed*, the remaining charge of HFC/PFC escapes to the atmosphere, is recycled, or possibly destroyed.

The need to update equipment inventories on an annual basis can be a major implementation challenge for inventory agencies with limited resources. The bottom-up method does not require annual chemical consumption data, however, although it could be used as a quality assurance check if available.

Tier 2b – Top-down approach

The top-down approach also estimates emissions from assembly, operation, and disposal, but does not rely on emission factors. Instead, the method uses measured consumption (i.e. sales) of each chemical in the country or facility being considered. The general equation is as follows[39]:

Equation 3.34

Emissions = Annual Sales of New Gas – (Total Charge of New Equipment – Original Total Charge of Retiring Equipment)

Industry purchases new chemical from manufacturers to replace leakage (i.e. emissions) from the current equipment stock, or to make a net change in the size of the total charge of the equipment stock.[40] The total

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[38] As approximately twenty different HFC and PFC chemicals could potentially be used as substitutes for ozone depleting substances, and emissions sources are numerous and extremely diversified, implementing the bottom-up method involves dealing with high volumes of data and levels of complexity.

[39] Boundary conditions: If there is no net change in the total equipment charge, then annual sales are equal to emissions. If the net change in the total equipment charge is equal to annual sales, then emissions are zero.

charge of new equipment minus the original total charge of retiring equipment represents the net change to charge of the equipment stock. Where the net change is positive, some of the new chemical is being used to satisfy the increase in the total charge, and therefore cannot be said to replace emissions from the previous year.

Using this approach, it is *not* necessary to know the total amount of each chemical in equipment stock in order to calculate emissions. One only needs to know the total charges of the new and retiring equipment. This approach is most directly applicable to the refrigeration and mobile air conditioning, and fire protection sub-source categories. Further elaboration and modification of this approach is provided in the description of each sub-source category. In addition, models are being developed that allocate chemical sales for different end uses into different regions of the world. These models are currently being derived for specific ODS Substitute end uses such as foam and fire protection.[41]

CHOICE OF EMISSION FACTORS

The type of emission factor required depends on the Tier 2 approach implemented.

Tier 2a – Bottom-up approach

For the bottom-up approach, specific emission factors are required to estimate emission rates from the major equipment types and sectors. Emission factors should be based on a country-specific study of the equipment units in stock to determine their remaining service lives, average charges, retrofit rates, leak rates, disposal quantities, and recovery practices. The *IPCC Guidelines* include default values for some of these parameters, but these are not country-specific. *Good practice guidance* provides additional default values for some sub-source categories.

A common theme is that management of the disposal of equipment at the end of its service life can have a profound effect on the total emissions. The chemical remaining in systems (called the ‘bank’) can be up to 90% of the original quantity used. Specific issues related to emission factors are discussed in the sub-source category sections.

Tier 2b – Top-down approach

As discussed above, the top-down approach generally relies on chemical sales data and does not use equipment-based emission factors. Where there are exceptions to this rule, *good practice guidance* is provided in each sub-source category section (e.g. fugitive emissions during the filling of equipment with HFCs and PFCs).

CHOICE OF ACTIVITY DATA

Tier 2a – Bottom-up approach

The bottom-up approach requires an inventory of existing HFC/PFC in existing units (i.e. the ‘bank’). Some inventory agencies may have access to national data published in trade magazines or technical reports. However, it is more likely that a study will be necessary to estimate the inventory of existing units or chemicals. Expert panels can also facilitate the generation of this information. Inventory agencies may also decide to conduct annual studies to update their inventories of sector units. An alternative to this may be to calculate or estimate production growth for each one of the sub-source categories under consideration. Data need to reflect new units that are introduced each year, and old or poorly functioning units that are retired.

Tier 2b – Top-down approach

Activity data for the top-down approach focus on chemical deployment rather than sources of emissions. For certain end-uses, such as fire protection and foam, global models are being developed that allocate accurately known production data into end-uses in specific regions. The activity data from these models will be particularly useful for countries with significant imports of chemical and equipment.

For the sales-based approach, data on national chemical use are more easily obtained than data for the national inventory of equipment responsible for emissions. It is *good practice* to obtain data on the total annual sales from the gas manufacturers or importers.[42] The best source of data on the total charge of new equipment is likely to be

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[40] Industry also requires new chemical to replace destroyed gas and for stockpiles. Terms can be added to the general equation to account for these uses; these terms are not included here for simplicity.

[41] For example, see www.greenhousegases.org.

[42] Tier 1b method of the *IPCC Guidelines,* Vol. 3, Section 2.17.3.3, provides the default method for annual sales data.

the equipment manufacturers or the trade associations that represent them. For the total charge of retiring equipment, one must know or estimate (i) equipment lifetime, and (ii) either (a) the historical sales of equipment and the equipment's historical average charge size, or (b) the growth rate of such sales and charge sizes.

Inventory agencies in countries that import all or the majority of new chemicals consumed are likely to encounter different issues of data availability than those in countries with significant domestic chemicals production. If the majority of chemicals are imported, either in bulk or in equipment and products, some form of import data will be necessary for calculating emissions. Ideally, customs officials should track and make available chemical import statistics. For some products, such as foam and aerosols, it may not be possible for customs officials to track the type of chemical in the product (e.g. CFCs vs. HFCs in aerosols), or the presence of the product in the imported equipment (e.g. closed cell foam in automobile seats). In such cases, it may be necessary to collect or estimate data with the assistance of major distributors and end-users.

COMPLETENESS

Completeness, in terms of the total quantity of chemical that could potentially be emitted, is covered by the fact that activity data for the top-down approach are recorded in terms of the quantity of chemical used. Completeness is an important issue for countries that use the Tier 2 bottom-up equipment-based method.

A fraction of new chemical production escapes to the atmosphere during production of each substance. Fugitive emissions from production are not accounted for in either of the Tier 2 methods (or the Tier 1 method). It is *good practice* for inventory agencies in countries with domestic chemical production to include fugitive emissions in their inventories. The suggested approach is to apply an emission factor to chemical production, or to assume that a fixed (additional) percentage of chemical sales was emitted during production. Although the default factor is 0.5%, experience in Japan shows much larger emissions.[43] It is *good practice* to determine the actual emission factor for each plant.

DEVELOPING A CONSISTENT TIME SERIES

Inventory agencies that have prepared potential (Tier 1) estimates in the past are encouraged to develop the capacity to prepare Tier 2 estimates in the future. It is *good practice* that actual and potential estimates are not to be included in the same time series, and that inventory agencies recalculate historical emissions with the actual method, if they change approaches. If data are unavailable, the two methods should be reconciled to ensure consistency, following the guidance on recalculation provided in Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques. It is *good practice* to fully document recalculation, ensuring transparency.

Emission factors generally come from historical data on other chemicals (e.g. CFCs) used in established markets and need to be adapted to new chemicals (e.g. ODS substitutes) in start-of-life markets. National data on base year deployment is now available (or can be calculated with known uncertainty).

UNCERTAINTY ASSESSMENT

Over a long time (greater than 20 years) emissions of ODS substitutes within a country will tend to equal total consumption in the same time frame. For a given year, the quantification of uncertainty for ODS is very difficult to estimate, due to the large number of different sources and the diversity of emission patterns. For the top-down Tier 2 method, the overall uncertainty will be directly related to quality and completeness of chemical sales and import data. For the bottom-up Tier 2 method, the uncertainty will reflect the completeness of the equipment survey, and the appropriateness of the emission functions developed to characterise emissions. Further advice on uncertainties is provided in the separate sections on the seven sub-source categories that follow.

Reporting and documentation for all ODS substitutes sub-source categories

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving.

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[43] Source: The Sixth Meeting of the Committee for Prevention of Global Warming and The Chemical Products Council of Japan, 21 May 1999.

As discussed above, inventory agencies should prepare and report actual emissions estimates for as many end use sub-source categories as possible. For those sub-source categories where it is not possible to prepare actual emissions estimates, inventory agencies should prepare and report potential emissions estimates. Inventory agencies reporting an actual/potential hybrid approach should include a set of potential estimates for each sub-source category so that total ODS substitute emissions can be calculated. As noted above, actual and potential estimates should not be summed together.

The balance between preservation of confidentiality and transparency of the data needs to be carefully addressed. Careful aggregation may solve some problems but will require that results are validated by other means (e.g. third party audit). Where data have been aggregated to preserve the confidentiality of proprietary information, qualitative explanations should be provided to indicate the method and approach for aggregation.

Inventory quality assurance/quality control (QA/QC) for all ODS substitutes sub-source categories

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source categories. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation. In addition to the guidance in Chapter 8, specific procedures of relevance to this source category are outlined below.

Comparison of emissions estimates using different approaches

Inventory agencies should use the Tier 1 potential emissions method for a check on the Tier 2 actual estimates. Inventory agencies may consider developing accounting models that can reconcile potential and actual emissions estimates and may improve determination of emission factors over time.

Inventory agencies should compare bottom-up estimates with the top-down Tier 2 approach, since bottom-up emission factors have the highest associated uncertainty. This technique will also minimise the possibility that certain end-uses are not accounted for in the bottom-up approach.

National activity data check

For the Tier 2a (bottom-up) method, inventory agencies should evaluate the QA/QC procedures associated with estimating equipment and product inventories to ensure that they meet the general procedures outlined in the QA/QC plan and that representative sampling procedures were used. This is particularly important for the ODS substitutes sub-sectors because of the large populations of equipment and products.

For the Tier 2b (top-down) method, inventory agencies should evaluate and reference QA/QC procedures conducted by the organisations responsible for producing chemical deployment information. Sales data may come from gas manufacturers, importers, distributors, or trade associations. If the QC associated with the secondary data is inadequate, then the inventory agency should establish its own QC checks on the secondary data, reassess the uncertainty of the emissions estimates derived from the data, and reconsider how the data are used.

Emission factors check

Emission factors used for the Tier 2a (bottom-up) method should be based on country-specific studies. Inventory agencies should compare these factors with the default values. They should determine if the country-specific values are reasonable, given similarities or differences between the national source category and the source represented by the defaults. Any differences between country specific factors and default factors should be explained and documented.

3.7.1 Aerosols sub-source category

3.7.1.1 Methodological issues

Most aerosol packages contain hydrocarbon (HC) as propellants but, in a small fraction of the total, HFCs and PFCs may be used as propellants or solvents. Emissions from aerosols usually occur shortly after production, on average six months after sale. During the use of aerosols, 100% of the chemical is emitted (Gamlen *et al.*, 1986, USA EPA, 1992a). The 5 main sources are as follows:

(i) Metered Dose Inhalers (MDIs);

(ii) Personal Care Products (e.g. hair care, deodorant, shaving cream);

(iii) Household Products (e.g. air-fresheners, oven and fabric cleaners);

(iv) Industrial Products (e.g. special cleaning sprays, lubricants, pipe-freezers);

(v) Other General Products (e.g. silly string, tire inflators, claxons).

The HFCs currently used as propellants are HFC-134a, HFC-227ea, and HFC-152a. The substance HFC-43-10mee and a PFC, perfluorohexane, are used as solvents in industrial aerosol products.[44]

CHOICE OF METHOD

Aerosol emissions are considered ‘prompt’ because all the initial charge escapes within the first year or two after sale. Therefore, to estimate emissions it is necessary to know the total amount of aerosol initially charged in product containers prior to sale. Emissions of each individual aerosol in year t can be calculated according to the *IPCC Guidelines* as follows:

Equation 3.35

$$\begin{gathered}\text{Emissions of HFCs in year t} = \\ [(\text{Quantity of HFC and PFC Contained in Aerosol Products Sold in year t}) \bullet (\text{EF})] \\ + [(\text{Quantity of HFC and PFC Contained in Aerosol Products Sold in year } (t-1)] \bullet (1-\text{EF})]\end{gathered}$$

This equation should be applied to each chemical individually. Total carbon equivalent emissions are equal to the sum of the carbon equivalent emissions of each chemical.

Since the lifetime of the product is assumed to be two years, any amount not emitted during the first year must by definition be emitted during the second and final year. In reality, most emissions occur within the first year of product purchase, but this calculation accounts for the lag period from time of purchase to time of use.[45] A decision tree for estimating actual emissions is included in Figure 3.12, Decision Tree for Actual Emissions (Tier 2) from the Aerosol Sub-source Category. The data collection process is described below.

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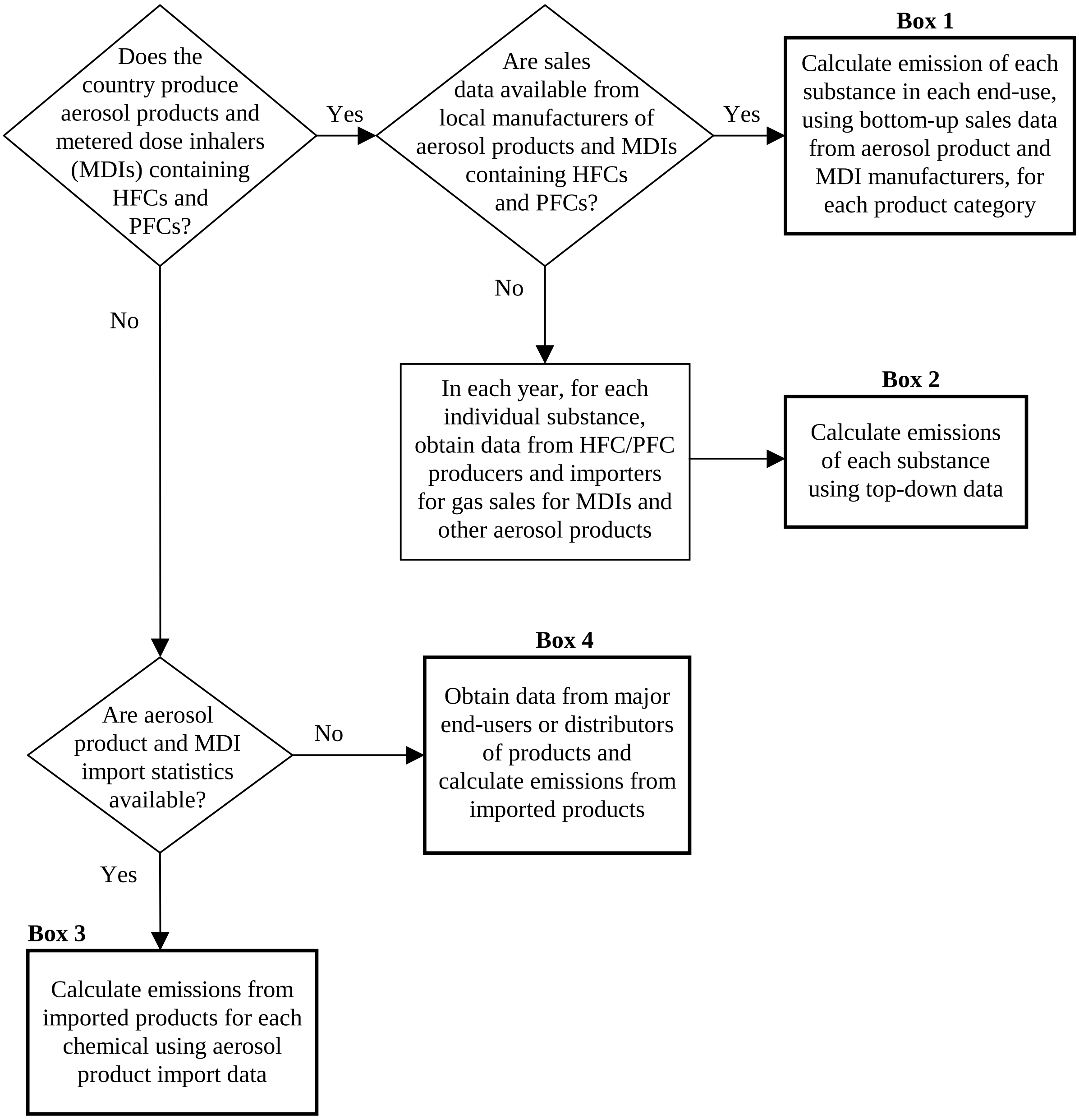
[44] HFC-43-10mee is used solely as a solvent, but is counted as an aerosol when delivered through aerosol canisters.

[45] For short-lived sources such as MDIs and aerosol products, the estimate of potential emissions is equivalent to using an emission factor of 100%. This will produce a result similar to the actual approach if there is no substantial growth in aerosol sales.

Figure 3.12 Decision Tree for Actual Emissions (Tier 2) from the Aerosol Sub-source Category



CHOICE OF EMISSION FACTORS

It is *good practice* to use a default emission factor of 50% of the initial charge per year for the broad spectrum of aerosol products. This means that half the chemical charge escapes within the first year and the remaining charge escapes during the second year (Gamlen *et al.*, 1986). Inventory agencies should use alternative emission factors only when empirical evidence is available for the majority of aerosol products. In any event, the percentage emission factors should in general sum to 100% over the time during which it is assumed that the charge will escape. The development of country-specific emission factors should be documented thoroughly. General aerosol and MDI manufacturers may be able to provide data on process losses.

CHOICE OF ACTIVITY DATA

The activity data required are the total quantity of each relevant chemical contained in all aerosol products consumed within a country (both domestic sales and imports). For countries that import 100% of aerosol products, activity data are equal to imports.

Activity data for this end use sub-source category can be collected using either a bottom-up or a top-down approach, depending on the availability and quality of the data. The bottom-up approach requires data on the number of aerosol products sold and imported (e.g. number of individual metered dose inhalers, hair care products, and tire inflators), and the average charge per container. The top-down approach involves collecting aerosol and MDI chemical sales data directly from chemical manufacturers. In many cases, a mix of bottom-up and top-down data may be necessary.

Domestic aerosol production: For countries with domestic production, general aerosol and MDI manufacturers can provide data on the quantity of aerosol products produced for consumption in the country, the number of aerosols exported, the average charge per aerosol, and the type of propellant or solvent used (i.e. which HFC/PFC). Total use of domestically produced aerosol products in each year can then be calculated as the number of aerosol products sold domestically in a given year times the charge of HFC/PFC in each product. If bottom-up data are not available, domestic chemical producers can provide data on the amount of HFCs sold to domestic manufacturers in metered dose inhalers, and aggregate sales data to producers of other aerosols (categories 2, 3, 4 and 5 above). If domestic aerosol and MDI manufacturers import HFCs, information may also be sought from chemical exporters, although they may not be able to provide data on exports destined for individual countries because of confidential business concerns. Customs officials and chemical distributors are another possible source for chemical import data.

Imported aerosol production: Most countries will import a significant share of their total aerosol products. Data on imports of HFC-containing general aerosols may be difficult to collect because official import statistics for aerosol products do not typically differentiate HFC-containing aerosols from others. When usable import statistics are unavailable from customs agencies, data may be available from product distributors and specific end-users. For example, in the case of MDIs, a limited number of pharmaceutical companies typically import products, and these companies can be surveyed to obtain the required information.

COMPLETENESS

Completeness depends on the availability of activity data. Inventory agencies in countries without domestic aerosol production may need to use expert judgement in estimating activity data, because import statistics are likely to be incomplete (see Chapter 6, Quantifying Uncertainties in Practice, Section 6.2.5, Expert Judgement).

DEVELOPING A CONSISTENT TIME SERIES

Emissions from aerosols should be calculated using the same method and data sources for every year in the time series. Where consistent data are unavailable for any year in the time series, gaps should be recalculated according to the guidance provided in Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques.

UNCERTAINTY ASSESSMENT

The use of HFCs in the general aerosol sector is larger than in the MDI sector. Data from HFC manufacturers and importers of sales to the general aerosol sector are, at the present time, not well defined other than for HFC-134a on a global scale. These data can be improved through additional data collection activities. The diffuse nature of the general aerosol sector means that the acquisition of reliable bottom-up data requires specific study on a country basis through local industry experts, whose advice should be sought on uncertainties using the approaches to expert judgement outlined in Chapter 6, Quantifying Uncertainties in Practice.

There are several sources of reliable data for the MDI sector, leading to a high level of confidence in the data reported that should be reflected in inventory emissions estimates. However, in reporting for a single country, the absence of reliable data for the general aerosol sector could mean that emission data could be over or under estimated by a factor of between one third and three times.

3.7.1.2 Reporting and documentation

The emission estimate for metered dose inhalers should be reported separately from the emission estimate for other aerosols. Inventory agencies should document the emission factor used. If a country-specific emission factor rather than the default factor is used, its development should be documented. Detailed activity data should be reported to the extent that it does not disclose confidential business information. Where some data are confidential, qualitative information should be provided on the types of aerosol products consumed, imported, and produced within the country. It is likely that the type of HFC used as a propellant or solvent and the sales of MDIs and general aerosols into individual countries could be viewed as confidential.[46] Where there are less than three manufacturers of specific chemicals used as solvents, reporting could be aggregated into this section, because both are considered 100% emissive applications (see Section 3.7.2.2 below).

3.7.1.3 Inventory quality assurance/quality control (QA /QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, Section 8.7, Source Category-specific QC Procedures (Tier 2), and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

In addition to the guidance in Chapter 8, Quality Assurance and Quality Control, specific procedures of relevance to this sub-source category are outlined as follows. Both bottom-up and top-down data should be used as a check on the emission estimate. Data used to calculate emissions from year t–1 should be consistent with data used in the previous year’s inventory estimate, so the two-year total sums to 100%. If this is not the case, then the reason for the inconsistency should be reported. Collection of the data described in the section on data collection above should provide adequate quality control. To allow independent assessment of the level of quality of the data reporting, the number of manufacturers of aerosols plus end users should be quantified.

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[46] Quantification of use data for individual general aerosol sectors will enable more reliable future projections to be developed and emission reduction strategies to be considered.

3.7.2 Solvents sub-source category

3.7.2.1 Methodological issues

HFCs and PFCs are used as solvents in four main areas as follows:

(i) Precision Cleaning;

(ii) Electronics Cleaning;

(iii) Metal Cleaning;

(iv) Deposition applications.

The use of HFCs as solvents is still in its infancy. Solvents that have been or may be used include HFC43-10mee, perfluorohexane (a PFC) and others that were not listed in the IPCC Second Assessment Report, including HFC-365mfc.[47]

CHOICE OF METHOD

As is the case in the aerosol sector, emissions from solvent applications generally are considered 'prompt' emissions because 100% of the chemical is emitted within two years. To estimate emissions it is necessary to know the total amount of chemical in solvent products sold each year. Emissions of HFCs and PFCs from solvent use in year t can be calculated according to the *IPCC Guidelines* as follows.

EQUATION 3.36

$$\begin{aligned}\text{Emissions in year t} = & \ [(\text{Quantity of Solvents Sold in year t}) \bullet \text{EF}] \\ & + [\text{Quantity of Solvents Sold in year } (t-1) \bullet (1-\text{EF})]\end{aligned}$$

As with aerosols, the equation should be applied to each chemical individually, depending on the disaggregation in available data. Moreover, the equation may also be applied to different equipment classes. Total carbon equivalent emissions are equal to the sum of carbon equivalent emissions of each chemical.

The emission factor EF represents the fraction of chemical emitted from solvents in year t. The product lifetime is assumed to be two years, and thus any amount not emitted during the first year must by definition be emitted during the second and final year. A decision tree for estimating actual emissions is included in Figure 3.13, Decision Tree for Actual Emissions (Tier 2) from the Solvents Sub-source Category. The data collection process is described below.

CHOICE OF EMISSION FACTORS

Good practice is to use a default emission factor of 50% of the initial charge/year for solvent applications.[48] In certain applications with new equipment, it is possible that much lower loss rates will be achieved and that emissions will occur over a period of more than two years. Alternative emission factors can be developed in such situations, using bottom-up data on the use of such equipment and empirical evidence regarding alternative emission factors.[49] Such country-specific emission factors should be documented thoroughly.

Modifications for the recovery and recycling of solvents should not be applied. While HFC and PFC solvents may be recovered and recycled several times during their use due to their high costs, in most emissive end uses the chemical will be released on average six months after sale.

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[47] The *IPCC Guidelines* provide 'Reporting Instructions' only for greenhouse gases with global warming potentials listed in the Second Assessment Report.

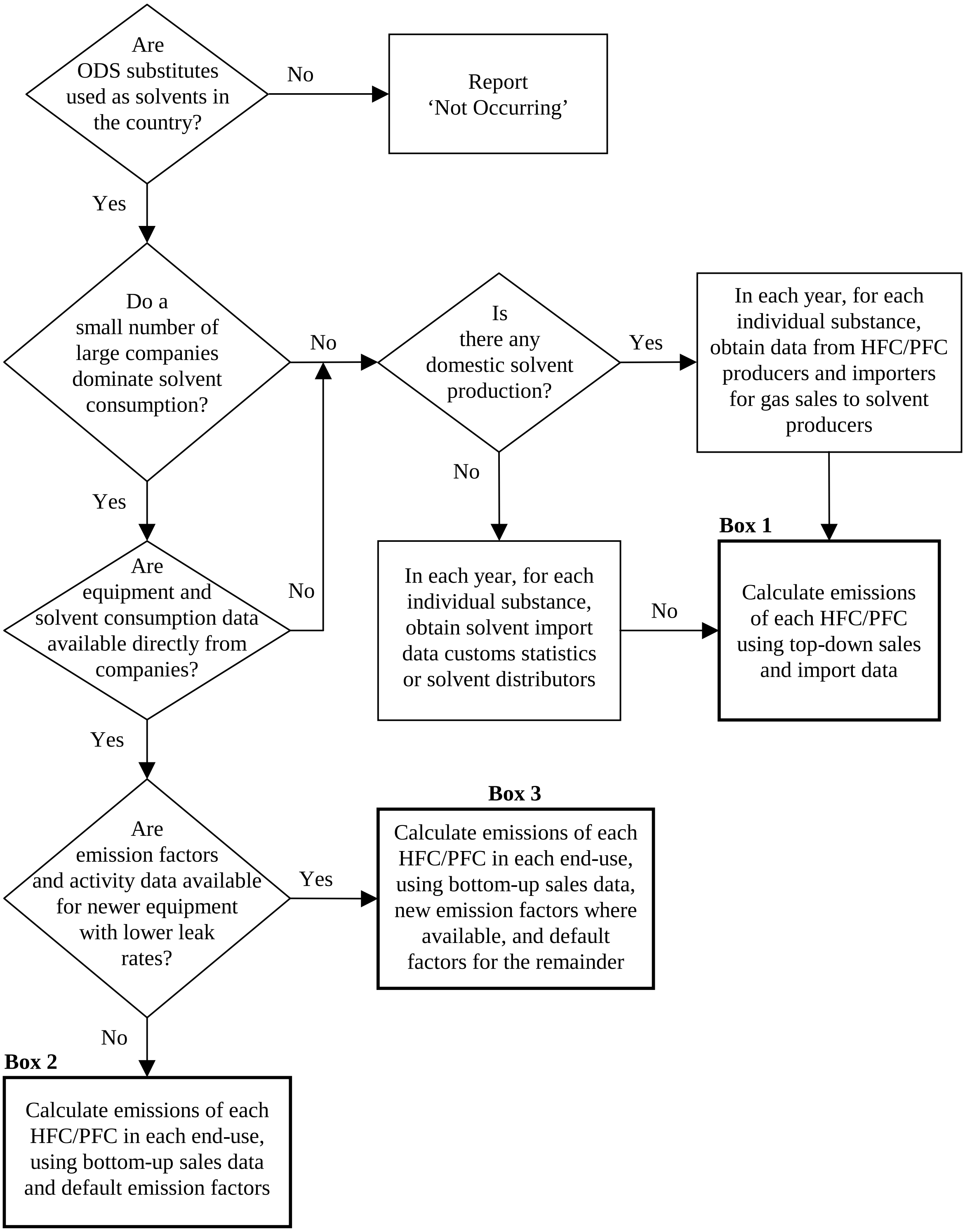
[48] See footnote 47.

[49] As guidance, for sales to new equipment, approximately 10-20% will be emitted with the rest of the gas banked. In subsequent years sales are for servicing volumes and can be considered 100% emitted.

CHOICE OF ACTIVITY DATA

The activity data for this end-use are equal to the quantity of each relevant chemical sold as solvent in a particular year. As with aerosols, data on both domestic and imported solvent quantities should be collected. The required data can be collected using either top-down or bottom-up methods, depending on the character of the national solvent industry. In most countries, the end-users will be extremely diverse and a top-down approach would be practical.

Figure 3.13 Decision Tree for Actual Emissions (Tier 2) from the Solvents Sub-source Category



Top-down data

Top-down data are equal to the amount of chemical solvent sold or imported annually into a country. Domestic solvent sales should be available directly from chemical manufacturers. As solvents are only produced in a few countries, most countries will import some or all of their consumption. Data on imported solvents can be collected from the exporting manufacturers, although information on exports to individual countries may be considered confidential. Alternatively, import statistics from customs agencies or the distributors of imported solvents can be used. Solvent import data are generally more easily obtained than aerosol import data because solvent is usually imported in bulk rather than in small containers.

If specific emission factors are developed for particular types of equipment, it will be necessary to disaggregate the consumption data into these equipment classes. In general, this will require a bottom-up approach.

Bottom-up data

Bottom-up activity data include the number of pieces of equipment or canisters containing solvent and their charge. The bottom-up approach is suitable where large corporations consume most of the solvent sold, because it should be possible to obtain detailed solvent end-use data from a few large entities. The bottom-up approach may also be most appropriate when equipment-specific emission factors are available.

COMPLETENESS

Completeness depends on the availability of activity data. Inventory agencies in countries without domestic solvent production may need to use expert judgement in estimating activity data, because import statistics are likely to be incomplete (see Chapter 6, Quantifying Uncertainties in Practice, Section 6.2.5, Expert Judgement).

DEVELOPING A CONSISTENT TIME SERIES

Emissions from foam should be calculated using the same method and data sources for every year in the time series. Where consistent data are unavailable for any years in the time series, gaps should be recalculated according to the guidance provided in Chapter 7, Methodological Choice and Recalculation.

UNCERTAINTY ASSESSMENT

The default assumption that all solvent is emitted within two years is widely accepted and should not lead to a significant error. Similarly, the activity data should be reliable because of the small number of chemical manufacturers, the high cost of the gas leading to little stockpiling, and the 100% emissive nature of the use in most applications.

3.7.2.2 Reporting and documentation

Inventory agencies should report the emission factor used, and the empirical basis for any country-specific factors. For activity data, chemical sales and imports should be reported, unless there are confidentiality concerns due to the limited number and location of manufacturers. (At present, for example, there may be only one producer of each compound.) Where there are less than three manufacturers of specific chemicals used as solvents, reporting could be aggregated into the aerosol section, because both are considered 100% emissive applications (see Section 3.7.1.2 above). In this case, to preserve confidentiality, emissions of individual gases should not be specified and emissions should be reported in CO_2-equivalent tonnes.

3.7.2.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, Section 8.7, Source Category-specific QC Procedures (Tier 2), and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

In addition to the guidance in Chapter 8, Quality Assurance and Quality Control, specific procedures of relevance to this source category are outlined below:

- For accurate quality control/assurance both top-down and end-use data should be compiled. To allow independent assessment of the level of quality of the data reporting, the number of manufacturers and distributors plus end users interviewed should be quantified.
- When applying emission factors and activity data specific to various solvent applications, the activity data should be obtained at the same level of detail.

3.7.3 Foam sub-source category

3.7.3.1 Methodological issues

Increasingly, HFCs are being used as replacements for CFCs and HCFCs in foam applications such as insulating, cushioning, and packaging. Compounds that may be used include HFC-245fa, HFC-365mfc, HFC-134a, and HFC-152a. For open-cell foam, emissions of HFCs used as blowing agents are likely to occur during the manufacturing process. In closed-cell foam, emissions occur over a longer time period (e.g. 20 years).

CHOICE OF METHOD

The decision tree in Figure 3.14, Decision Tree for Actual Emissions (Tier 2) from the Foam Sub-source Category, describes *good practice* methods in estimating emissions.

The *IPCC Guidelines* suggest calculating emissions from open-cell foam separately from emissions from closed-cell foam:

Open-Cell Foam: Since HFCs and PFCs used for open-cell foam blowing are released immediately, all of the emissions will occur in the country of manufacture. Emissions are calculated according to the following equation, as presented in the *IPCC Guidelines*:[50]

Equation 3.37

$$\text{Emissions from Open-cell Foam} = \text{Total Annual HFCs and PFCs Used in Manufacturing Open-cell Foam}$$

Closed-Cell Foam: Emissions from closed-cell foam occur at three distinct points:

(i) First Year Losses from Foam Manufacture and Installation: These emissions occur where the product is manufactured.

(ii) Annual Losses (in-situ losses from foam use): Closed-cell foam will lose a fraction of their initial charge each year until decommissioning. These emissions occur where the product is used.

(iii) Decommissioning Losses: Emissions upon decommissioning also occur where the product is used.

Section 2.17.4.3 of the *IPCC Guidelines*, Vol.3, Estimation of Emissions of HFCs and PFCs from Foam Blowing, presents an equation for calculating emissions from the foam blowing that accounts for the first two emission points. In order to prepare a complete estimate of emissions from this source, it is *good practice* to add a third term to the equation to account for decommissioning losses and chemical destruction, where data are available. Thus, the suggested equation is:

Equation 3.38

$$\begin{aligned}\text{Emissions from Closed-cell Foam} = {} & [(\text{Total HFCs and PFCs Used in Manufacturing New Closed-cell Foam in year t}) \bullet (\text{first-year Loss Emission Factor})] \\ & + [(\text{Original HFC or PFC Charge Blown into Closed-cell Foam Manufacturing between year t and year t} - \text{n}) \bullet (\text{Annual Loss Emission Factor})] \\ & + [(\text{Decommissioning Losses in year n}) - (\text{HFC or PFC Destroyed})]\end{aligned}$$

Where:

n = Product lifetime of closed-cell foam

Decommissioning losses = the remaining chemical at the end of service life that occur when the losses equipment is scrapped

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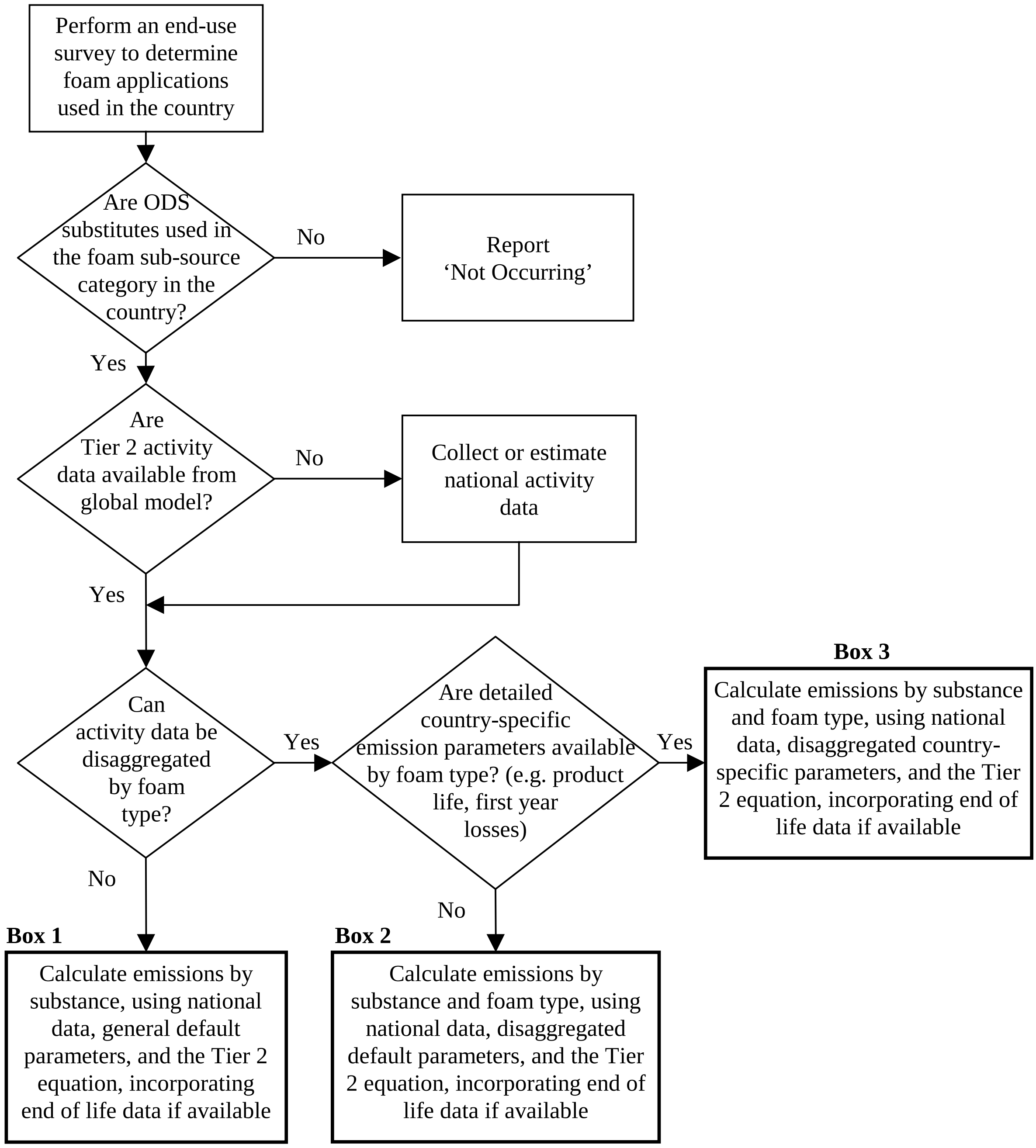
[50] For these applications, actual emissions of each chemical are equal to potential emissions.

This equation should be applied to each chemical and major foam application individually. Total CO_2-equivalent emissions are equal to the sum of CO_2-equivalent emissions of each combination of chemical type and foam application.

To implement this approach it is necessary to collect current and historical data on annual chemical sales to the foam industry for the period up to and including the average lifetime of closed-cell foam (e.g. the most recent twenty years). If it is not possible to collect data for potential losses upon decommissioning, it should be assumed that all chemical not emitted in manufacturing is emitted over the lifetime of the foam.

A modification of this approach is to use activity data provided by a global model that allocates accurately known production data to the different foam applications in various regions around the world. These data can then be used with the disaggregated emission factors provided in Table 3.17, Default Emission Factors for HFC/PFC from Closed-Cell Foam.

Figure 3.14 Decision Tree for Actual Emissions (Tier 2) from the Foam Sub-source Category



CHOICE OF EMISSION FACTORS

As in other sub-source categories, the first choice for emission factors is to develop and use peer-reviewed and well documented country-specific data based on field research. As noted previously, if no information is available for decommissioning losses, then the emission factors used for first-year and annual losses should account for all chemical consumption.[51]

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[51] It has also been noted that decommissioning may not necessarily involve total loss of blowing agent at that point, either because of a level of secondary use or because the item has been discarded intact (e.g. many refrigerators). These could be considered as some of the end-of-life management options available to nations, but are clearly less effective than proper destruction or recovery technologies. Future emission models should focus proper attention to end-of-life issues.

If country-specific data are not available, default assumptions can be used. Table 3.18, Default Emission Factors for HFC-134a Applications (Foam Sub-source Category) – (Derived from existing CFC/HFC information accumulated through national/international research), and Table 3.19, Default Emission Factors for HFC-245a/HFC-365mfc Applications (Foam Sub-source Category) – (Derived from existing CFC/HFC information accumulated through national/international research), present state-of-the-art *good practice* emission factors assumptions for the most important current closed-cell foam applications. Use of these factors will require data on chemical sales and the bank of chemical in equipment for these applications.

If only aggregated chemical sales data for closed-cell foam are available and information on specific foam types cannot be obtained, the general default emission factors listed in the *IPCC Guidelines* should be used.[52] These general default emission factors are shown in Table 3.17, Default Emission Factors for HFC/PFC from Closed-Cell Foam.

TABLE 3.17
DEFAULT EMISSION FACTORS FOR HFC/PFC FROM CLOSED-CELL FOAM

Emission Factor	**Default Values**
Product Lifetime	n = 20 years
First Year Losses	10% of the original HFC or PFC charge/year, although the value could drop to 5% if significant recycling takes place during manufacturing.
Annual Losses	4.5% of the original HFC or PFC charge/year

Source: Gamlen *et al.* (1986).

TABLE 3.18
DEFAULT EMISSION FACTORS FOR HFC-134A APPLICATIONS (FOAM SUB-SOURCE CATEGORY)
(DERIVED FROM EXISTING CFC/HFC INFORMATION ACCUMULATED THROUGH NATIONAL/INTERNATIONAL RESEARCH)

HFC-134a Applications	**Product Life in years**	**First Year Loss %**	**Annual Loss %**
Polyurethane – Integral Skin[a]	12-15	95	2.5
Polyurethane – Continuous Panel	50	10	0.5
Polyurethane – Discontinuous Panel	50	12.5	0.5
Polyurethane – Appliance	15-20	7.5	0.5
Polyurethane – Injected	15	12.5	0.5
One Component Foam (OCF) [a]	50	95	2.5
Extruded Polystyrene/ Polyethylene (XPS/PE) [a]	50	40	3

[a] HFC-152a Applications.

Source: Ashford (1999).

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[52] No emission factors are provided for open-cell foams because all emissions occur during the first year.

TABLE 3.19
DEFAULT EMISSION FACTORS FOR HFC-245A/HFC-365MFC APPLICATIONS (FOAM SUB-SOURCE CATEGORY) – (DERIVED FROM EXISTING CFC/HFC INFORMATION ACCUMULATED THROUGH NATIONAL/INTERNATIONAL RESEARCH)

HFC-245a/HFC-365mfc Applications	Product Life in years	First Year Loss %	Annual Loss %
Polyurethane – Continuous Panel	50	7.5	0.5
Polyurethane – Discontinuous Panel	50	10	0.5
Polyurethane – Appliance	15	4	0.25
Polyurethane – Injected	15	10	0.5
Polyurethane – Continuous Block	15	40	0.75
Polyurethane – Discontinuous Block	15	45	0.75
	50	10	1
Polyurethane – Continuous Laminate	25	10	1
Polyurethane – Spray	50	25	1.5
Phenolic – Discontinuous Block	15	45	0.75
Phenolic – Discontinuous Laminate	50	10	1

Source: Ashford (1999).

Use of these default emission factors will result in 90% of the initial charges being emitted over twenty years of annual use, after the initial 10% during the first year.

CHOICE OF ACTIVITY DATA

Two types of activity data are needed in order to prepare the emissions estimates: the amount of chemical used in foam manufacturing in a country, and the amount of chemical contained in foam used in the country. Data collection issues related to these two areas differ.

- ***Chemical Used in Foam Manufacture***: The amount of bulk chemicals used in the foam blowing industry should include both domestically produced and imported HFCs and PFCs. Domestic chemical sales data to the foam industry should be available directly from chemical manufacturers. As with other ODS substitute sub-source categories, imported chemical data may be available from customs officials or chemical distributors.

For open-cell foam, all emissions will occur during manufacture. Thus, it is necessary to determine the share of chemical associated with the manufacture of open-celled foam. These data can be determined through an end-use survey, or approximated by reviewing similar end-use data gathered on CFCs and HCFCs.

- ***Chemical Emitted During the Lifetime of Closed-Cell Foam***: Annual decommissioning losses associated with closed-cell foam should be calculated for all the foam in use in the country. This will require consideration of the import and export of products containing closed-cell foam which can be quite complicated.

Inventory agencies in countries that export closed-cell foam should subtract these volumes from their calculations of annual and decommissioning losses, since the emissions will occur in the importing country. Data on the chemical charge of exported closed-cell foam may be available from large manufacturers.

Inventory agencies in countries that import products containing closed-cell foam, in contrast, should include estimates of emissions from these imported products for completeness. Since import statistics for closed-cell foam products are extremely difficult to collect, inventory agencies in countries whose emissions occur only from imported closed-cell foam may need to use expert judgement in estimating this data (see Chapter 6, Quantifying Uncertainties in Practice, Section 6.2.5, Expert Judgement).

In the future, inventory agencies may be able to use international HFC/PFC production and consumption data sets to develop estimates of chemical contained in imported closed-cell foam. For example, the Alternative Fluorocarbon Environmental Assessment Study (AFEAS) statistics-gathering process compiled global activity data up until 1997 for HFC-134a in the foam sector.[53] Although the global data are relatively well understood, regional breakdowns are not presently available.

COMPLETENESS

Fifteen foam applications and four potential chemicals used as blowing agents (HFC-134a, HFC-152a, HFC-245fa and HFC-365mfc) have been identified in the foam sub-source category. For completeness, inventory agencies should determine whether the blowing agents are used in each application, which suggests 60 theoretically possible combinations (see Table 3.20, Use of ODS Substitutes in the Foam Blowing Industry). In practice, this list reduces to 32 realistic potential chemical/application combinations, although there are some potential regional variations. It should also be noted that, at this stage, the method does not address the potential use of blends and, in reality, it would be difficult to assign different emission factors to such systems. The main problem with the potential use of blends will be one of activity monitoring.

TABLE 3.20
USE OF ODS SUBSTITUTES IN THE FOAM BLOWING INDUSTRY
(FOAM PRODUCT EMISSIONS BY GAS – ODS REPLACEMENTS)

Sub-sectors	**HFC Foam Blowing Agent Alternates**[b]			
	HFC-134a	**HFC-152a**	**HFC-245fa**	**HFC-365mfc**
PU[a] Flexible Foam	X	X	X	X
PU Flexible Molded Foam	X	X	X	X
PU Integral Skin Foam	O	O	X	X
PU Continuous Panel	O	X	O	O
PU Discontinuous Panel	O	X	O	O
PU Appliance Foam	O	X	O	O
PU Injected Foam	O	X	O	O
PU Continuous Block	X	X	O	O
PU Discontinuous Block	X	X	O	O
PU Continuous Laminate	X	X	O	O
PU Spray Foam	X	X	O	O
PU One Component Foam	O	O	X	X
Extruded Polystyrene/Polyethylene	O	O	X	X
Phenolic Block	X	X	O	O
Phenolic Laminate	X	X	O	O

[a] PU = Polyurethane.
[b] X – no anticipated use, O – current or anticipated use.

DEVELOPING A CONSISTENT TIME SERIES

An inventory agency should maintain a consistent method in assessing its emissions over the time period. If, for example, no system is established to monitor actual decommissioning at the outset of the inventory process, it will be very difficult to obtain data retrospectively if a change from 'default' to 'actual' data is considered. This decision should therefore be the subject of careful consideration at the outset of the reporting process. Any recalculation of estimates should be done according to the guidance provided in Chapter 7.

UNCERTAINTY ASSESSMENT

Current sales data indicate that the global estimates are accurate to within 10%, regional estimates are in the 30-40% range, and the uncertainty of country specific top-down information may be more than 50% (McCulloch,

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[53] HFC-134a is the most commonly used HFC. AFEAS data can found at http://www.afeas.org.

1986). The application of emission factors will add to the uncertainties, particularly if only default emissions can be used, although it should be noted that the calculation of the total emissions for a year will be only partially dependent on the accuracy of assumptions for new consumption in that year. The remainder of the emissions will arise from installed foam and from those decommissioned in that year. Since decommissioning will be the trigger for the majority of emissions in many cases, the product life assumptions may introduce the greatest degree of uncertainty in the default emissions calculations. It is therefore very important that inventory agencies keep records of their estimates of HFC containing products and develop some mechanism for monitoring actual decommissioning if possible. These records may help ensure that the summed emissions do not exceed total inputs over time.

3.7.3.2 Reporting and documentation

Emissions factors should be reported, along with documentation for the development of country-specific data. Chemical sales to the foam blowing industry should be reported in a manner that preserves confidential business information. Most confidentiality issues arising from any data collection process relate to the most highly concentrated activities. To deal with this, emissions from foam could be reported as a single number, provided that the development of the number could be reviewed under suitable terms of confidentiality. Of course, a declaration of consolidated emissions from manufacture (first year), use (product life) and decommissioning (end-of-life) will always be preferable to allow continued focus on improvements being made in each of these areas. If, in the future, inventory agencies use the global and regional data sets, they should report the results of how they allocated emissions to the country level.

3.7.3.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, Section 8.7, Source Category-specific QC Procedures (Tier 2), and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

One of the main concerns will be to ensure that the preservation of the integrity of regional and global data will be maintained by the summation of individual country estimates and a major part of the QA/QC review process will need to concern itself with this cross reference.

3.7.4 Stationary refrigeration sub-source category

3.7.4.1 Methodological issues

HFCs and PFCs are used as replacements for CFCs and HCFCs in refrigeration and stationary air conditioning equipment. Examples of refrigeration equipment include household refrigerators, retail food refrigeration, commercial and residential air conditioning, and cold storage warehouses. For the time being this sub-source category also includes transport refrigeration, other than that covered in the Mobile Air-conditioning sub-source category (see Section 3.7.5, Mobile Air-conditioning Sub-source Category).[54]

CHOICE OF METHOD

The Tier 2 approach in the *IPCC Guidelines* is based on calculating emissions from assembly, operation, and disposal of stationary refrigeration equipment. The general equation is shown below:

EQUATION 3.39

$$\text{Total Emissions} = \text{Assembly Emissions} + \text{Operation Emissions} + \text{Disposal Emissions}$$

- ***Assembly emissions*** include the emissions associated with product manufacturing, even if the products are eventually exported.
- ***Operation emissions*** include annual leakage from equipment stock in use as well as servicing emissions. This calculation should include all equipment units in the country, regardless of where they were manufactured.
- ***Disposal emissions*** include the amount of refrigerant released from scrapped systems. As with operation emissions, they should include all equipment units in the country where they were scrapped, regardless of where they were manufactured.

Good practice is to implement a top-down Tier 2 approach, using annual sales of refrigerant. The alternative approach, using bottom-up equipment data and multiple emission factors, is much more data intensive and is unlikely to improve accuracy, but it is still *good practice* under certain national circumstances. The decision tree in Figure 3.15 Decision Tree for Actual Emissions (Tier 2) from the Refrigeration Sub-source Category, describes *good practice* methods in estimating emissions. Table 3.22, Best Estimates (expert judgement) for Charge, Lifetime and Emission Factors for Stationary Refrigeration Equipment, describes the emission factors for the top-down and bottom-up approaches and the improvements to the default data in the Tier 2 method.

Top-down approach

For the top-down approach, the three emission stages are combined into the following simplified equation:

EQUATION 3.40

$$\begin{aligned}\text{Emissions} = {} & (\text{Annual Sales of New Refrigerant}) - (\text{Total Charge of New Equipment}) \\ & + (\text{Original Total Charge of Retiring Equipment}) - (\text{Amount of Intentional Destruction})\end{aligned}$$

Annual Sales of New Refrigerant is the amount of a chemical introduced into the refrigeration sector in a particular country in a given year. It includes all the chemical used to fill or refill equipment, whether the chemical is charged into equipment at the factory, charged into equipment after installation, or used to recharge equipment at servicing. It does not include recycled chemical.

Total Charge of New Equipment is the sum of the full charges of all the new equipment that is sold in the country in a given year. It includes both the chemical required to fill equipment in the factory and the chemical required to fill the equipment after installation. It does not include charging emissions or chemical used to recharge equipment at servicing.

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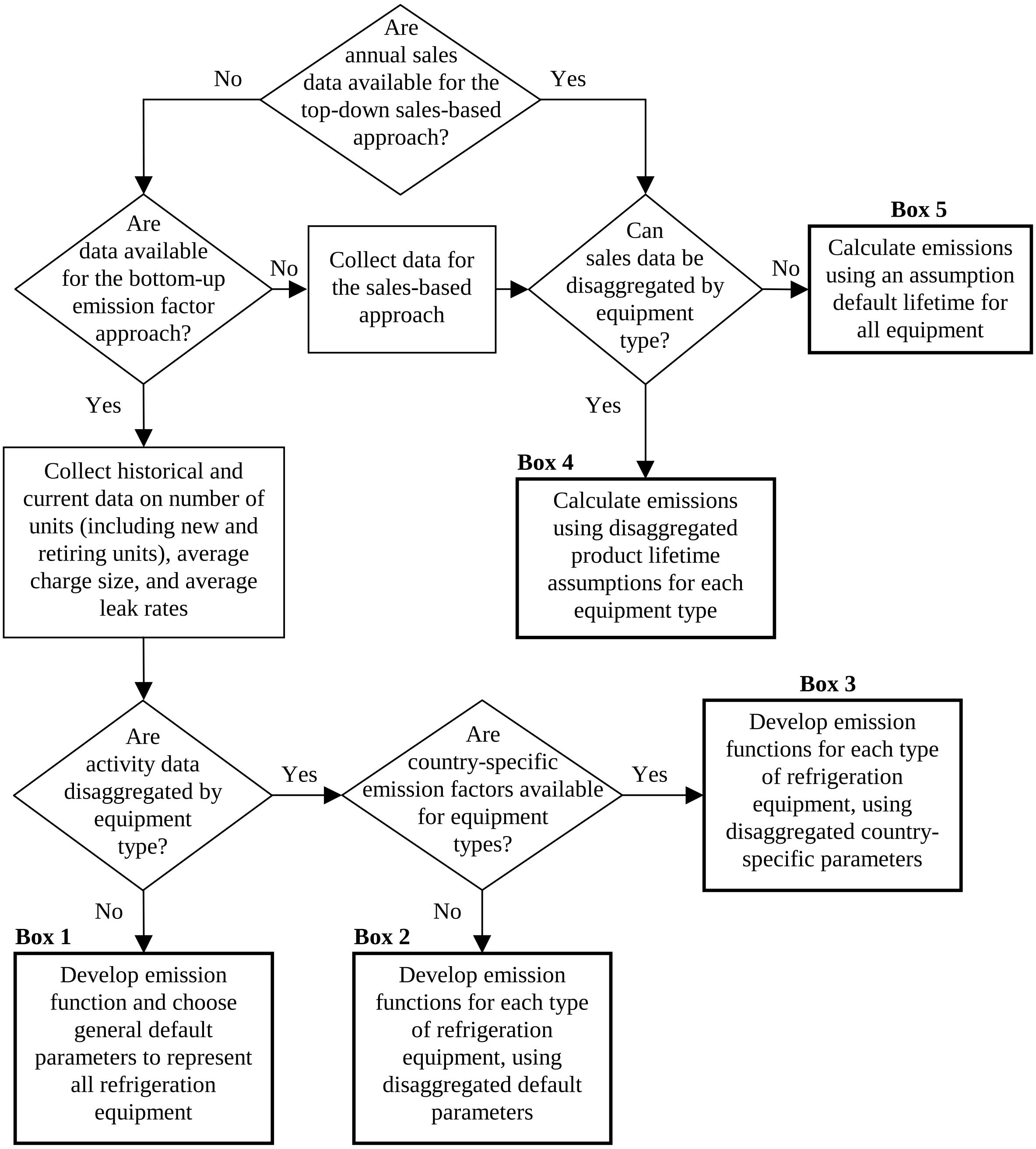
[54] Particularly self-contained systems; engine driven system should be covered as mobile air conditioning (see Section 3.7.5, Mobile Air-conditioning Sub-source Category).

Figure 3.15 Decision Tree for Actual Emissions (Tier 2) from the Refrigeration Sub-source Category



Original Total Charge of Retiring Equipment is the sum of the original full charges of all the equipment that are retired in the country in a given year. It includes both the chemical that was originally required to fill equipment in the factory and the chemical that was originally required to fill the equipment after installation. It does not include charging emissions or chemical used to recharge equipment at servicing.

In each country there is a stock of existing refrigeration equipment that contains an existing stock of refrigerant chemical (bank). Therefore, annual sales of new chemical refrigerant must be used for one of two purposes:[55]

- To increase the size of the existing chemical stock (bank) in use; or
- To replace that fraction of last year's stock of chemical that was emitted to the atmosphere (through, for example, leaks and disposal).

The difference between the total quantity of gas sold and the quantity of that gas used to increase the size of the chemical stock equals the amount of chemical emitted to the atmosphere. The increase in the size of the chemical stock is equal to the difference between the total charges of the new and retiring equipment.

By using data on current and historical sales of gas, rather than emission factors referenced from literature, the equation reflects assembly, operation, and disposal emissions at the time and place where they occur. Default emission factors are likely to be inaccurate because emissions rates may vary considerably from country to country and even within a single country.

This equation can be applied either to individual types of equipment, or more generally to all air conditioning and refrigeration equipment in a country, depending on the level of disaggregation of available data. If disaggregated data are available, emissions estimates developed for each type of equipment and chemical are summed to determine total emissions for sector.

Bottom-up approach

Implementing the bottom-up Tier 2 approach requires an estimation of the amount of refrigerant in the stock of equipment, and emission factors to represent equipment various types of leakage (i.e. assembly, operation, and disposal emissions):

For assembly emissions, the following equation should be used:

EQUATION 3.41

$$\text{Assembly Emissions} = (\text{Total HFC and PFC Charged in year } t) \bullet (k / 100)$$

Where:

k = Emission factor that represents the percentage of initial charge that is released during assembly

Operation emissions are calculated from the total bank of HFCs/PFCs contained in equipment presently in use. The following equation should be used:

EQUATION 3.42

$$\text{Operation Emissions} = (\text{Amount of HFC and PFC Stock in year } t) \bullet (x / 100)$$

Where:

x = Annual leak rate as a percentage of total charge. Since different types of refrigeration equipment will leak at different rates, *good practice* is to disaggregate data into homogeneous classes (i.e. by age or size) and develop values of x specific to different types of equipment

To calculate disposal emissions, it is necessary to know the average lifetime (n) of equipment and the initial charge n years ago. Disposal emissions can then be calculated according to the following equation:

EQUATION 3.43

$$\text{Disposal Emissions} = (\text{HFC and PFC Charged in year } t - n) \bullet (y / 100) \bullet (1 - z / 100) - (\text{Amount of Intentional Destruction})$$

Where:

y = Percentage of the initial charge remaining in the equipment at the time of disposal

z = Recovery efficiency at the time of disposal. If any chemical is recycled during disposal, the percentage should be subtracted from the total. If there is no recycling, this term will be zero

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[55] Industry also requires new chemicals for stockpiles. A term can be added to the general equation to account for this use; this term is not included here for simplicity.

CHOICE OF EMISSION FACTORS

Top-down approach (sales-based)

As this approach is based on chemical sales and not equipment leak rates, it does not require the use of emission factors.

Bottom-up approach

Good practice for choosing bottom-up emission factors is to use country-specific data, based on information provided by equipment manufacturers, service providers, and disposal companies. When national data are unavailable, inventory agencies should use the default emission factors shown in Table 3.22, Best Estimates (expert judgement) for Charge, Lifetime and Emission Factors for Stationary Refrigeration Equipment , which summarises best estimates of equipment charge, lifetime, and emission factors. These default values reflect the current state of knowledge about the industry, and are provided as ranges rather than point estimates. Inventory agencies should choose from the range according to country-specific conditions, and document the reasons for their choices. If bottom-up data cannot be broken down into the equipment classes as in Table 3.21, Good Practice Documentation for Stationary Refrigeration , it is *good practice* to use expert judgement to estimate the relative share of each type of equipment, and choose default emission factors appropriate to the most common types of equipment (see Chapter 6, Quantifying Uncertainties in Practice, Section 6.2.5, Expert Judgement).

CHOICE OF ACTIVITY DATA

Top-down approach (sales-based)

Inventory agencies in countries that manufacture refrigerant chemicals should estimate *Annual Sales of New Refrigerant* using information provided by chemical manufacturers. Data on imported chemical should be collected from customs statistics, importers, or distributors. (See Box 3.4 for a discussion of how to treat imports and exports in estimating *Annual Sales* and the other quantities in the equation.)

Total Charge of New Equipment can be estimated using either:

- Information from equipment manufacturers/importers on the total charge of the equipment they manufacture or import; or
- Information from chemical manufacturers/importers on their sales to equipment manufacturers.

The first data source may be preferable to the second because some new equipment may not be charged by the equipment manufacturers, while some of the refrigerant sold to equipment manufacturers may not be used to fill new equipment (e.g. because it is used to service existing equipment).

Original Total Charge of Retiring Equipment can be estimated using the same sources as are used for *Total Charge of New Equipment.* In this case, however, the data are historical, coming from the year in which this year’s retiring equipment was built. That year is determined by subtracting the lifetime of the equipment from the current year. Information on equipment lifetimes can be gathered from equipment manufacturers and users. Default values for the lifetimes of seven different types of equipment are provided in Table 3.22, Best Estimates (expert judgement) for Charge, Lifetime and Emission Factors for Stationary Refrigeration Equipment. The default product lifetime value for air-conditioning and refrigeration equipment as a whole, for use when data for specific types of equipment are not available, is 10-15 years.

COMPLETENESS

Completeness for the top-down method is achievable if data for new refrigerant, and refrigerant in equipment being retired in the current year are available. For the bottom-up method, completeness depends on a thorough accounting of the existing equipment stock that may involve tracking large amounts of data.

DEVELOPING A CONSISTENT TIME SERIES

Emissions from stationary refrigeration should be calculated using the same method and data sources for every year in the time series. Where consistent data are unavailable for the more rigorous method for any years in the time series, these gaps should be recalculated according to the guidance provided in Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques.

BOX 3.4
ACCOUNTING FOR IMPORTS AND EXPORTS OF REFRIGERANT AND EQUIPMENT

In estimating *Annual Sales of New Refrigerant, Total Charge of New Equipment*, and *Original Total Charge of Retiring Equipment*, inventory agencies should account for imports and exports of both chemicals and equipment. This will ensure that they capture the actual domestic consumption of chemicals and equipment. For example, if a country imports a significant share of the HFC-134a that it uses, the imported quantity should be counted as part of **Annual Sales**. Alternatively, if a country charges and then exports a significant number of household refrigerators, the total charge of the exported refrigerators should be subtracted from the total charge of the household refrigerators manufactured in the country to obtain Total Charge of New Equipment.

GENERAL APPROACH: In general, the quantity Annual Sales should be estimated using the following formula:

Annual Sales =	**Domestically Manufactured Chemical**	**+ Imported Bulk Chemical**	**– Exported Bulk Chemical**	**+ Chemical Contained in Factory-Charged Imported Equipment**	**– Chemical Contained in Factory-Charged Exported Equipment**

All quantities should come from the year for which emissions are being estimated. Similarly, the quantity of Total Charge of New Equipment should be estimated using the following:

Total Charge of New Equipment=	**Chemical to Charge Domestically Manufactured Equipment**	**+ Chemical to Charge Imported Equipment that is not Factory-Charged**	**+ Chemical Contained in Factory-Charged Imported Equipment**	**– Chemical Contained in Factory-Charged Exported Equipment**

Original Total Charge of Retiring Equipment should be estimated the same way as *Total Charge of New Equipment,* except all quantities should come from the year of manufacture or import of the retiring equipment.

SIMPLIFIED APPROACH: In estimating Annual Sales and Total Charge of New Equipment, it is possible to ignore the quantities of chemical imported or exported inside of factory-charged equipment because these quantities cancel out in the calculation of emissions. However, inventory agencies that use the simplified calculation should ensure that: (1) they treat imports and exports of factory-charged equipment consistently in estimating both Annual Sales and Total Charge New of Equipment; and (2) they continue to account for imports and exports of factory-charged equipment in estimating Original Total Charge of Retiring Equipment. As new equipment will eventually become retiring equipment, countries may wish to track imports and exports of factory-charged equipment even if this information is not strictly necessary to develop the current year's estimate.

The simplified formula for **Annual Sales** is:

Annual Sales =	**Domestically Manufactured Chemicals**	**+ Imported Bulk Chemicals**	**– Exported Bulk Chemicals**

The simplified formula for **Total Charge of New Equipment** is:

Total Charge of New Equipment =	**Chemicals to Charge Domestically Manufactured Equipment**	**+ Chemicals to Charge Imported Equipment that is not factory-charged**

The full formula, accounting for imports and exports of pre-charged equipment, must be used to calculate *Original Total Charge of Retiring Equipment***.**

UNCERTAINTY ASSESSMENT

Table 3.22, Best Estimates (expert judgement) for Charge, Lifetime and Emission Factors for Stationary Refrigeration Equipment, presents emission factor ranges that highlight the uncertainty associated with this sector. Generally, bottom-up actual methods that rely on emission factors have more uncertainty than top-down methods that use chemical sales data. Inventory agencies should seek industrial advice on uncertainties, using the approaches to obtaining expert judgements outlined in Chapter 6, Quantifying Uncertainties in Practice.

3.7.4.2 Reporting and documentation

The supporting information necessary to ensure transparency in reported emissions estimates is shown in Table 3.21, Good Practice Documentation for Stationary Refrigeration.

TABLE 3.21
GOOD PRACTICE DOCUMENTATION FOR STATIONARY REFRIGERATION

Good practice **Reporting Information by Method**	**Tier 2 (Top-Down)**	**Tier 2 (Bottom-Up)**
Total annual sales of new refrigerant	X	
Total charge of new equipment	X	X
Original total charge of retiring equipment	X	X
Total charge of entire equipment stock		X
Lifetime of equipment	X	X
Documentation for lifetime, if country-specific	X	X
Emission/recovery factors		X
Documentation for factors, if country-specific		X

Source: Judgement by Expert Group (see Co-chairs, Editors and Experts, Emissions of Substitutes for Ozone Depleting Substances).

3.7.4.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1, General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, Section 8.7, Source Category-specific QC Procedures (Tier 2), and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

In addition to the guidance in Chapter 8, Quality Assurance and Quality Control, specific procedures of relevance to this sub-source category are outlined as follows:

- Implementing both the bottom-up approach and the simplified top-down approach will enable a cross-check of the final emission estimate.
- It is particularly important to check the accuracy of emission factors used in the bottom-up method with top-down data, since emission factors are likely to have the highest associated uncertainty.

This technique will also minimise the possibility that certain end-uses will not be accounted for.

This is similar to the ‘Reference Approach’ calculation in the Energy Sector. The combination uses the simple top-down approach as a cross-check of a more detailed technology and application-based method.

TABLE 3.22
BEST ESTIMATES (EXPERT JUDGEMENT) FOR CHARGE, LIFETIME AND EMISSION FACTORS FOR STATIONARY REFRIGERATION EQUIPMENT

Application	**Charge (kg)**	**Lifetimes (years)**	**Emission Factors (% of initial charge/year)**		
Factor in Equation	**(Ei_{charge})**	**(n)**	**(k)**	**(x)**	**(z)**
			Initial Emission	**Lifetime Emission**	**End-of-Life Emission (recovery efficiency)**
Domestic Refrigeration	0.05 ≤ c ≤ 0.5	12 ≤ t ≤ 15	0.2 ≤ e ≤ 1	0.1 ≤ e ≤ 0.5	70% of remainder
Stand-alone Commercial Applications	0.2 ≤ c ≤ 6	8 ≤ t ≤ 12	0.5 ≤ e ≤ 3	1 ≤ e ≤ 10	70 ≤ r ≤ 80% of remainder
Medium & Large Commercial Refrigeration	50 ≤ c ≤ 2000	7 ≤ t ≤ 10	0.5 ≤ e ≤ 3	10 ≤ e ≤ 30	80 ≤ r ≤ 90% of remainder
Transport Refrigeration	3 ≤ c ≤ 8	6 ≤ t ≤ 9	0.2 ≤ e ≤ 1	15 ≤ e ≤ 50	70 ≤ r ≤ 80% of remainder
Industrial Refrigeration including Food Processing and Cold Storage	10 ≤ c ≤ 10K	10 ≤ t ≤ 20	0.5 ≤ e ≤ 3	7 ≤ e ≤ 25	80 ≤ r ≤ 90% of remainder
Chillers	10 ≤ c ≤ 2000	10 ≤ t ≤ 30	0.2 ≤ e ≤ 1	2 ≤ e ≤ 15	80 ≤ r ≤ 95% of remainder
Residential and Commercial A/C, including Heat Pumps	0.5 ≤ c ≤ 100	10 ≤ t ≤ 15	0.2 ≤ e ≤ 1	1 ≤ e ≤ 5	70 ≤ r ≤ 80% of remainder

Note: Distribution Losses = 2 to 10% of annual sales of refrigerant (heel left in the tanks from and losses during transfer (ICF 1998). Analysis of Refrigerant Emissions Resulting from Improper Disposal of 30-lb Cylinders. Prepared by ICF Incorporated, Washington, DC. June 2, 1998).
It should be noted that each country will use its own national data when preparing its national greenhouse gas inventory.

Source: Clodic (1999).

3.7.5 Mobile air-conditioning sub-source category

3.7.5.1 Methodological issues

The automotive industry has used HFC-134a for mobile air-conditioning (MAC) in new vehicles since 1995. Mobile air-conditioning provides cooling for passengers in cars, trucks, trains, trams and buses. In addition, some trucks cool their cargo area with an automotive system (compressor mounted to the engine) using HFC-134a.

In the past, the procedure for mobile air-conditioning systems has been to release the refrigerant to the atmosphere during service. The requirement for new refrigerant can be greatly reduced by implementing a refrigerant recovery/recycling program when servicing MACs.

CHOICE OF METHOD

The choice of *good practice* methods depends on national circumstances (see decision tree in Figure 3.16, Decision Tree for Actual Emissions (Tier 2) from the Mobile Air-conditioning Sub-source Category). The general Tier 2 approach for estimating emissions from all types of refrigeration and air conditioning units is outlined in the *IPCC Guidelines*, Vol. 3, Section 2.17.4.2, Estimation of Emissions of HFCs and PFCs from Use in Refrigeration and Air Conditioning Equipment, and also in the *good practice* description for stationary refrigeration. The general equation for Tier 2 is as follows:[56]

Equation 3.44

$$\text{Annual Emissions of HFC-134a} = \text{'First-Fill' Emissions} + \text{Operation Emissions} + \text{Disposal Emissions} - \text{Intentional Destruction}$$

First-Fill emissions include emissions of refrigerant released during the filling of all MAC units (potential future emissions) at the time of assembly by a vehicle manufacturer or the aftermarket MAC system installer in a country, even if the vehicles are eventually exported. Operation emissions include the annual leakage from all MACs in use in a country, including servicing emissions, regardless of where they were manufactured. Disposal emissions include the amount of refrigerant released from scrapped MAC systems.

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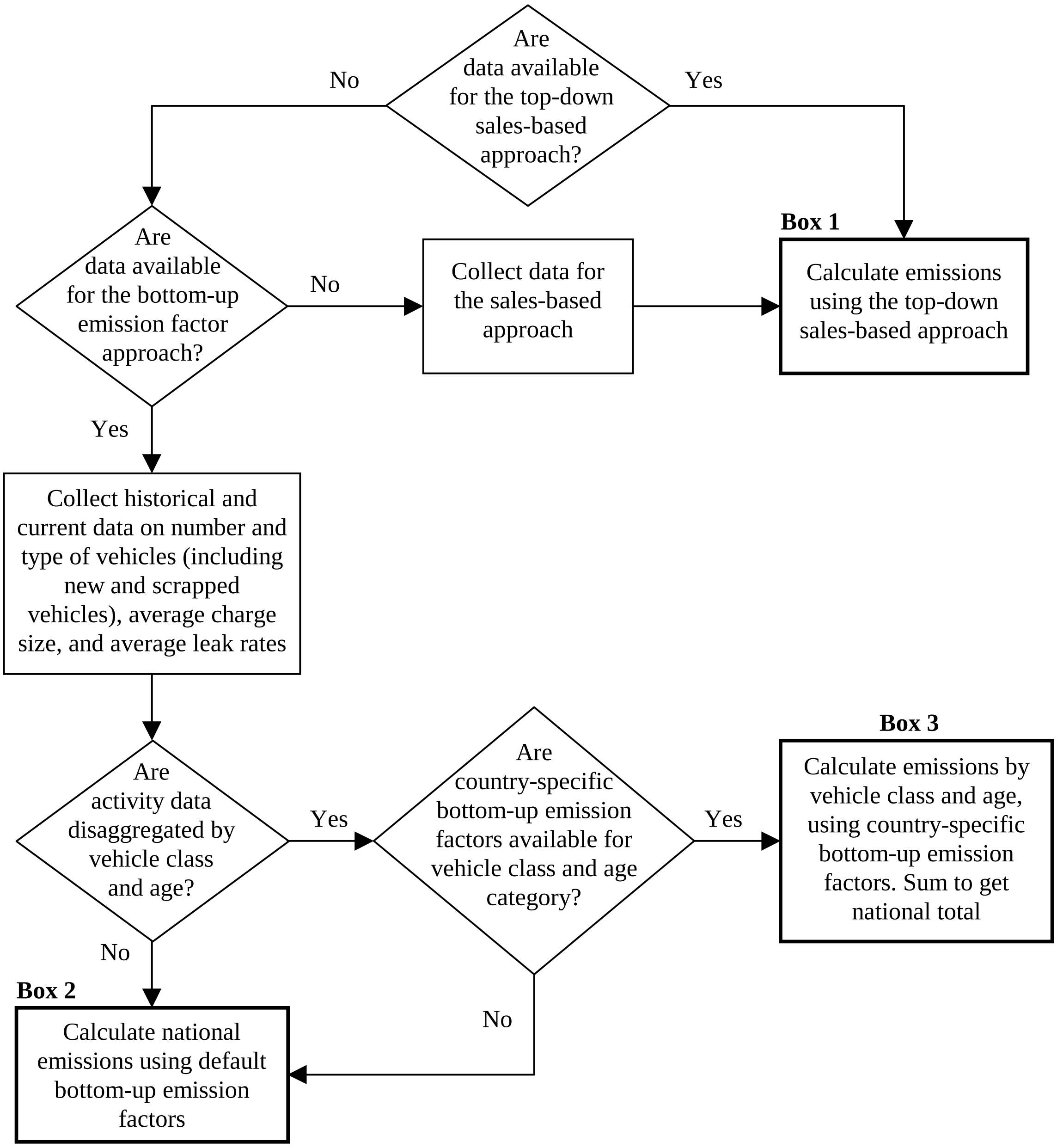
[56] For the purpose of this sub-source category, 'first-fill' emissions are equivalent to the term 'assembly' emissions as used in the stationary refrigeration sub-source category.

Figure 3.16 Decision Tree for Actual Emissions (Tier 2) from the Mobile Air-conditioning Sub-source Category



Top-down approach

The top-down Tier 2 approach is the most accurate method because it is less data intensive, uses more robust and reliable data, and requires fewer assumptions. The top-down approach estimates emissions by using chemical sales data to calculate the share of total HFC-134a sales used by the mobile air conditioning industry to replace refrigerant leaked to the atmosphere (e.g. car manufacturers, aftermarket installers and service companies). This value, when added to 'first-fill' and disposal emissions, is equal to total annual emissions. The top-down equation is presented at the end of this section in its complete form. Below, the equation is broken out into its constituent parts.

First-fill emissions are calculated by using an emission factor (EF) to represent the fraction of HFC-134a (e.g. 0.005) that escapes as fugitive emissions (assembly process loss) during equipment first fill:

EQUATION 3.45

$$\text{First-Fill Emissions} = (\text{EF}) \bullet (\text{Annual Virgin HFC-134a for First-Fill of New MAC Units})$$

Any new HFC-134a that did not escape as fugitives during first-fill, and did not go into new MAC units, must therefore be used for servicing existing units that leaked during operation in the previous year. Thus, operation emissions can be calculated according to following equation:

EQUATION 3.46

$$\begin{aligned}\text{Operation Emissions} = {} & (\text{Total Annual Virgin HFC-134a Sold to the MACs Industry}) \\ & - (\text{Total Annual Virgin HFC-134a for First-Fill of New MAC Units})\end{aligned}$$

Recycled and recovered refrigerant is implicitly accounted for in this equation because it reduces the amount of total virgin material needed in the country or region.[57]

Emissions occurring after the final service of MAC units are equal to the total amount of HFC-134a present in vehicles scrapped during the year, after subtracting any destruction. As a boundary condition, this equation would continue to estimate (vintage) emissions into the future even if no new HFC-134a were introduced into the MACs sector:

EQUATION 3.47

$$\begin{aligned}\text{Disposal Emissions} = {} & (\text{Annual Scrap Rate of Vehicles with MACs Using HFC-134a}) \\ & \bullet (\text{Number of Vehicles with MACs Using HFC-134a}) \\ & \bullet (\text{Average HFC-134a Charge/Vehicle}) - \text{Destruction}\end{aligned}$$

As noted previously, recovered and recycled HFC-134a captured during service or salvage should not be included in this equation, because it reduced the amount of virgin (new) HFC-134a needed in the country, and thus reduced emissions implicitly. Subtracting recovered and recycled HFC-134a at this point would lead to an underestimation of emissions.

Bottom-up approach

The Tier 2 method can also be implemented from the bottom-up, by estimating number of MAC units in the country, the average charge per vehicle, and applying emission factors that represent leak rates. The first-fill equation is similar to the top-down approach:

EQUATION 3.48

$$\text{First-Fill Emissions} = (\text{Total HFC-134a Charged in year t}) \bullet (k / 100)$$

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[57] Countries or regions that perform recycling during service and recovery at vehicle scrap would benefit significantly from reduced total emissions. Recycling at service and recovery at scrap can reduce total emissions by an estimated 60%.

The variable k is comparable to the variable EF used in the top-down approach because it represents the percentage of initial charge that is released during assembly.

EQUATION 3.49

$$\text{Operation Emissions} = (\text{Amount of HFC-134a Stock in year t}) \bullet (x / 100)$$

The emission factor x represents the annual emissions rate as a percentage of total charge. This equation should be applied for different types of MACs, because leak rates depend on the age and type of vehicles. Older MAC units are likely to have higher leak rates than new units. The total HFC-134a in the vehicle bank should include all systems in operation in the country. A recovery/recycling program for vehicle service and scrap will substantially reduce the requirement for new refrigerant.

To calculate disposal emissions, it is necessary to know the average lifetime (n) of vehicles, and the initial charge n years ago. Disposal emissions can then be calculated according to the following equation:

EQUATION 3.50

$$\text{Disposal emissions} = (\text{HFC-134a Charged in year } t - n) \bullet (y / 100) \bullet (1 - z / 100)$$

The variable y is the percentage of the initial charge remaining in MAC units at the time of disposal, and z equals the recovery efficiency at the time of disposal. If any refrigerant is recycled during disposal, the percentage should be subtracted from the total. If there is no recycling, z will be zero.

CHOICE OF EMISSION FACTORS

Top-down approach

The top-down approach only requires an emission factor for first-fill emissions. *Good practice* is to apply a factor of 0.5% (0.005)) if measured data are unavailable. Use of alternate assumptions should be fully documented.

Bottom-up approach

Inventory agencies using the bottom-up approach should make every effort to develop current country-specific values for the parameters x, n, k, y and z. If country-specific values are used, they must be fully documented. If country-specific values are unavailable, Table 3.23, Default Emission Parameters for ODS Substitutes from the MAC Sub-source Category (Bottom-up Approach), lists default emission parameters from the *IPCC Guidelines*, and updates for some parameters based on recent industry experience.

TABLE 3.23
DEFAULT EMISSION PARAMETERS FOR ODS SUBSTITUTES FROM THE MAC SUB-SOURCE CATEGORY (BOTTOM-UP APPROACH)

Bottom-up Emission Parameters	IPCC Default Values	Updated Default Values
Average vehicle lifetime (n)	12 years	12 years
MAC system emission rate (x)	10-30%	10-20%
First-Fill emission rate (k)	4-5%	0.5%
Typical remaining charge (y)	75%	40%
Fraction Recovered [a] (z)	0%	0%

[a] The fraction recovered by a recovery/recycling program is a function of the efficiency of the recovery equipment, the skill of the technician (amount of potential HFC-134a recovered/recycled) and the program effectiveness (fraction of service operations adopting the program).

Source: Baker (1999).

The MAC system emissions rate (x) is highly dependent on the presence of recovery and recycling programs. If a country has such a program, the low end of the range (i.e. 10%) is appropriate. Without a program, the value may be closer to 20%. The choice of system emission rate is tied to the choice of the fraction recovered (z). If a country has a recovery and recycling program, it is likely to reduce emissions both during service and at the end of the vehicle air-conditioning system lifetime. Consequently, the inventory agency in this country should use a recycling rate value greater than zero for z. Similarly, an inventory agency in a country without a recovery/recycling program should choose a higher value for x and a value of 0% for z.

Verification of emissions

The 'Top-Down' and 'Bottom-Up' results should agree within 10%.

CHOICE OF ACTIVITY DATA

Top-down approach

Under the top-down approach, activity data include the amount of HFC-134a sold to the MAC industry, the amount used for first-fill, the variables needed to determine the amount of HFC-134a in scrapped vehicles, and the amount of HFC-134a destroyed (if any). Data collection issues related to each term are discussed below.

- ***Total virgin HFC-134a*** includes only newly-produced refrigerant sold to MAC end-users. End-users include automobile manufacturers, aftermarket system installers, and repair shops that charge systems with refrigerant prior to sale. HFC-134a present in a refrigerant distributor's inventory, and refrigerant not sold for use in the mobile air-conditioning systems should not be included in the current year's estimate. If there is a large number of end-users, inventory agencies should obtain sales data directly from chemical manufacturers and refrigerant distributors. Data on imported virgin chemical should be available from customs officials, or importers and distributors.
- ***Total first fill HFC-134a*** is the total amount of HFC-134a purchased and used to charge new mobile air-conditioning systems by vehicle manufacturers (OEMs) or aftermarket MAC system installers. This includes losses during the charging process (First-Fill Emissions). In countries with domestic automobile industries, automobile manufacturers should be able to supply this data. Additional data should be available from installers of aftermarket air conditioning units.[58]
- ***Disposal emissions*****:** If the actual number of scrapped vehicles containing HFC-134a is unknown, it should be estimated on the basis of the *Vehicle Scrap Rate* that is the rate at which vehicles are taken out of service in the country or region. If possible, scrap rates should be disaggregated by model year, and the average scrap rate for the model years in which MACs were charged with HFC-134a should be applied. If the vehicle scrap rate cannot be obtained from vehicle registration statistics, the 8% can be used as a default value of the total fleet. The total number of registered vehicles in the country should be obtained from official government statistics. The share of the total fleet equipped with MACs can be obtained from vehicle manufacturers and importers. The penetration of HFC-134a into the MACs market should be estimated on the basis of industry expert judgement.
- ***The average HFC-134a charge*** is the weighted average of refrigerant charge in vehicles in the country. The default value in the *IPCC Guidelines* is 0.8 kg per vehicle.
- ***HFC-134a destruction*** is not widely practised at the present time. However, if an inventory agency has data on this practice, it should be included in the equation and documented to ensure that emissions are not overestimated.

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[58] When new automobiles are shipped, the refrigerant is considered to be in a container, (i.e. the mobile A/C system), and does not produce emissions.

Default parameters are shown below, in Table 3.24, Default IPCC Emission Parameters for ODS Substitutes from the MAC Sub-source Category (Top-down Approach):

TABLE 3.24
DEFAULT IPCC EMISSION PARAMETERS FOR ODS SUBSTITUTES FROM THE MAC SUB-SOURCE CATEGORY (TOP-DOWN APPROACH)

Top-down Emissions Parameters	Default Values
Average HFC-134a Charge	0.80 kg per vehicle [a]
Vehicle Scrap Rate	8%
Refrigerant released during new vehicle 'First Fill'	EF = 0.5% of average system charge

[a] This applies to passenger cars. A value of 1.2 kg/vehicle should be used for light trucks (Atkinson, 1999).

Source: Atkinson and Baker (1999).

Bottom-up approach

The bottom-up approach requires data on the amount of HFC-134a charged per year, the stock of HFC-134a in all MACs each year, and the amount remaining at the end of the MACs lifetime, as follows:

- The ***total HFC-134a*** used for first-filling of new MAC units is the same value needed for the top-down approach, and can be obtained from vehicle manufacturers, and aftermarket MAC installers.
- The ***stock of HFC-134a*** in operating vehicles during the year is equal to the number of vehicles in the total fleet using HFC-134a multiplied by the average charge per vehicle. This information should be available from annual data supplied by automobile manufacturers for the last n years. The default value of 0.8 kg/vehicle for the top-down approach can be used for the bottom-up approach as well, if fleet-specific data are not available.
- The ***amount of HFC-134a*** that was *originally* charged into MAC units n years ago should include units produced and charged domestically, as well as imported units. As with the total charge, determining original charges requires historical data on first-fill. Given that HFCs have only been used extensively in MACs in recent years, it is not necessary to go back more than a few years at this time to obtain the required data.

COMPLETENESS

For the top-down approach, it is not necessary to account for imported automobiles or imported air conditioning units because they are essentially 'containers'. Emissions from first-fill are accounted for in the country of manufacture. Once imported, however, emissions from imported vehicles are accounted for by the importing country based on the refrigerant used to service them, and by their 'post-service emissions' estimated from total vehicle registrations (that include imports). Similarly, it is not necessary to report exports as a separate class of systems because they are accounted for in the equation. Only processing emissions from first filling (0.5% of system charge) are charged to the country or region of manufacture in the equation, and all future emissions are accounted for by the importing country or region.

For the bottom-up approach, completeness will depend on the coverage of automobile activity data, particularly import data and data on after-market MAC units in operation.

DEVELOPING A CONSISTENT TIME SERIES

Emissions from mobile air-conditioning should be calculated using the same method and data sources for every year in the time series. Where consistent data are unavailable for the same method for any years in the time series, these gaps should be recalculated according to the guidance provided in Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques.

UNCERTAINTY ASSESSMENT

Uncertainty in the bottom-up approach will be considerably higher than that of the top-down approach because there are no internal checks to ensure that the accounting is complete. The top-down method provides an upper-bound, and thus the likelihood is low that the true value will exceed the top-down estimate. Inventory agencies should seek industrial advice on uncertainties, using the approaches to obtaining expert judgements outlined in Chapter 6, Quantifying Uncertainties in Practice.

3.7.5.2 Reporting and documentation

The background data in Table 3.25, Good Practice Documentation for Mobile Air-conditioning, should be collected and reported:

For the bottom-up method, it is important the inventory agencies report on the method of accounting for recovery of HFC-134a during service (i.e. choice of value x). The linkage with the value for fraction recovered (z) should be clearly documented.

3.7.5.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Tier 2 procedures in Chapter 8, and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

TABLE 3.25
GOOD PRACTICE DOCUMENTATION FOR MOBILE AIR-CONDITIONING

Data Source	Data to be Reported	Top-down	Bottom-up	Data Source[a]
Government Statistics	Number of scrapped vehicles	X	X	G
	Car registrations in the country	X	X	G
Refrigerant Distributors	All virgin HFC-134a sold to end users in the MACs market	X		I/G
Vehicle Manufacturers	All virgin HFC-134a purchased directly from refrigerant producers (Including imported HFC-134a)	X		I
	All refrigerant used for ‘First Fill’ of new HFC-134a A/C systems (t for the bottom-up method)	X	X	I
	Weighted average HFC-134a A/C system charge	X	X	I
	Vehicles sold and the percentage equipped with HFC-134a A/C systems	X	X	I
Vehicle Importers	The total number of vehicles imported and the percentage equipped with HFC-134a air-conditioning system	X	X	I/G
After-market System Manufacturers/Installers	All virgin HFC-134a used for ‘First Fill’ of new systems. (t for the bottom up method.)	X	X	I
	Number of HFC-134a A/C systems sold in the country or region	X	X	I/G
Manufacturers and installers of new systems	Actual process emissions if they differ significantly from the default emissions	X	X	I
Other Information for the Bottom-up Method	Fraction of HFC-134a recovered during disposal (z)		X	I/G
	Annual leakage rate for existing systems (x)		X	I
	Average vehicle lifetime (n)		X	I
	Initial Charge of systems in year t – n		X	I
	Amount of HFC-134a in systems at time of disposal (y)		X	I
	Initial charge of A/C systems in year t – n		X	I

[a] ‘I’ = Industry, ‘G’ = Government.

Source: Judgement by Expert Group (see Co-chairs, Editors and Experts, Emissions of Substitutes for Ozone Depleting Substances).

3.7.6 Fire protection sub-source category

3.7.6.1 Methodological issues

There are two general types of fire protection (fire suppresion) equipment that use halons, and their partial substitutes HFCs and PFCs: portable (streaming) equipment, and fixed (flooding) equipment. HFCs and PFCs are mainly used as substitutes for halons in flooding equipment.

CHOICE OF METHOD

Fire protection equipment is designed to release its initial charge during an actual fire incident. Studies have shown that annual use on fires accounts for less than 2% of the installed base. Other emissions resulting from leakage and accidental release account for less than 5% of the installed base on an annual basis. Due to the cost of the substance used as extinguishing agents and as the result of lessons learned from the phase-out of halons, a very high percentage (approximately 85%) of the HFCs and PFCs are typically recovered at the end of useful life of the equipment. The useful life of the fire protection equipment is usually based on the useful life of the application that is being protected. As fire protection systems that employ HFCs or PFCs are most commonly used to protect electronic equipment, useful life is normally less than 10 years, due to rapid changes in electronic equipment technology. The choice of *good practice* methods depends on national circumstances (see decision tree in Figure 3.17, Decision Tree for Emissions of ODS Substitutes from the Fire Protection Sub-source Category). The method in the *IPCC Guidelines* calculates emissions as a function of the HFCs and PFCs charged into new equipment during the year:

EQUATION 3.51

Emissions of HFCs or PFCs in year t = (HFCs/PFCs Used to Charge New Fire Protection Equipment) • (Emission Factor in Percent)

The emission factor represents the fraction of newly charged HFCs and PFCs released during the year. In reality, HFCs and PFCs are emitted over a period longer than one year, so this emission factor also represents emissions from equipment charged during previous years. Choosing an annual production-based emission factor to reflect a multi-year emission process can lead to considerable error.[59]

Good practice is to model emissions based on a top-down approach similar to that used by the Montreal Protocol Halons Technical Options Committee for estimating emissions of halons. However, until this model becomes available for use with ODS substitutes, the IPCC equation should be modified to account for equipment filled with HFCs and PFCs during previous years. With this modification, the equation is comparable to the top-down Tier 2 approach outlined for stationary refrigeration and mobile air conditioning: [60]

EQUATION 3.52

Emissions = Annual Sales of HFCs/PFCs for Fire Protection
– (HFCs/PFCs used to Charge New Fire Protection Equipment
– HFCs or PFCs Originally Used to Charge Retiring Fire Protection Equipment)

The difference between the annual quantity of each HFC/PFC sold to the fire protection industry, and the change in size of the total stock of each HFC/PFC, equals the amount of chemical emitted to the atmosphere. The change in stock of each HFC/PFC is equal to the difference between the total charges of the new and retiring equipment.

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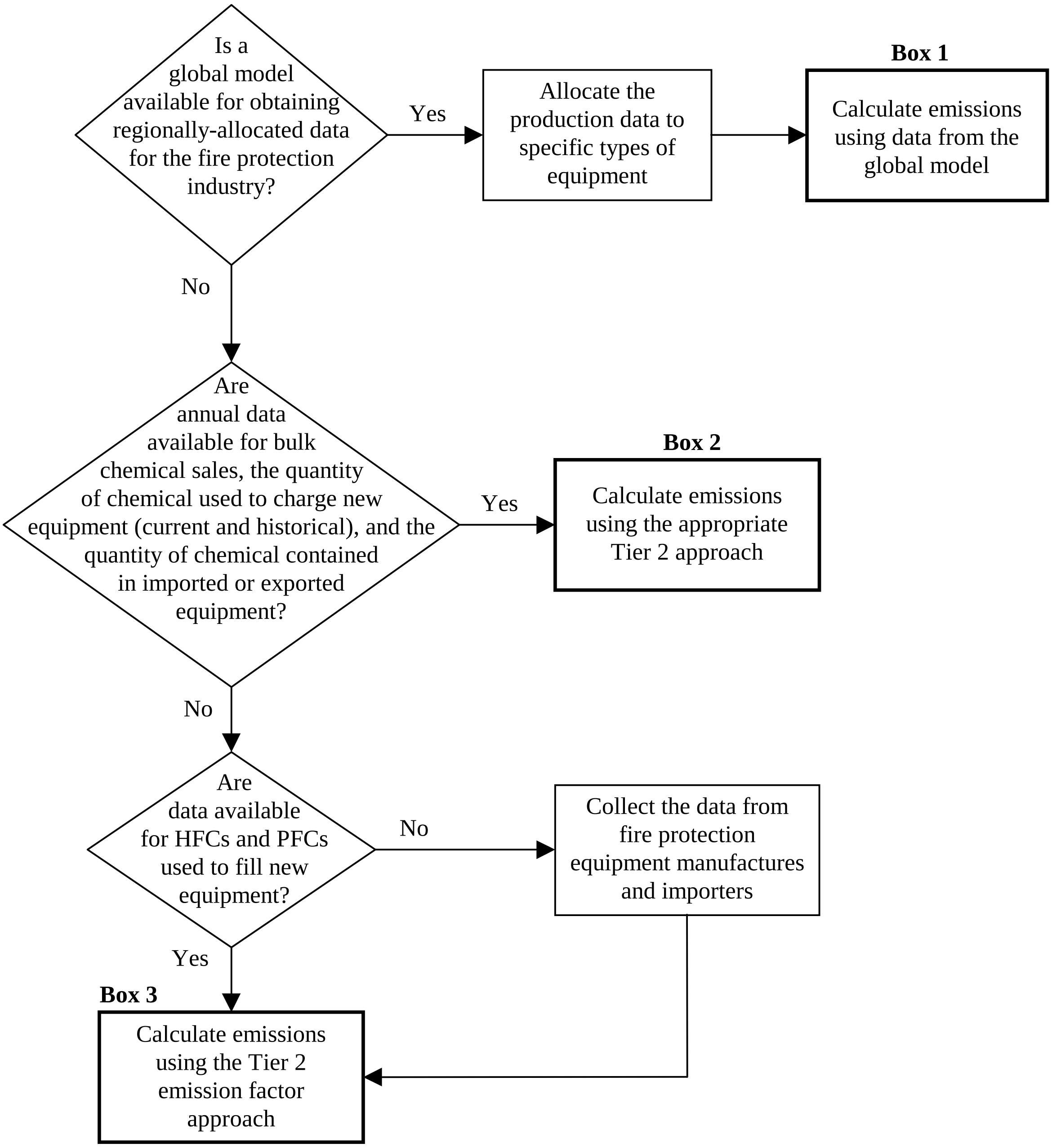
[59] The emissions rate as a function of the equipment base is more important than the emission rate as a function of production. As experienced with halons, when production ceased, the emissions did not cease but continued to follow a consistent pattern based on the equipment base.

[60] The sales-based approach as applied to the Fire Protection sub-source category is essentially the same approach as for the Stationary Refrigeration sub-source category.

This equation should be applied to each individual HFC/PFC used in fire protection equipment. Total carbon equivalent emissions are equal to the sum of carbon equivalent emissions of all HFCs and PFCs. Tracking of exports/imports of fire protection equipment that uses HFCs or PFCs is essential to ensure that the modified equation yields accurate emissions estimates.

A bottom-up Tier 2 approach is not suitable for the fire protection sub-source category because the required activity data do not exist for most countries. Existing customs codes and government statistics do not differentiate between equipment containing ODS substitutes and other compounds. For example, although a fire protection unit would be accounted for, at present there is no specific procedure to differentiate and account for those that use an ODS substitute versus another type of chemical.

Figure 3.17 Decision Tree for Emissions of ODS Substitutes from the Fire Protection Sub-source Category



CHOICE OF EMISSION FACTORS

The top-down Tier 2 method does not require emission factors. However, if activity data for previous years are unavailable and an emission factor is required, the default emission factors presented in the *IPCC Guidelines* and shown in Table 3.26, Default IPCC Emission Parameters for the Fire Protection Sub-source Category (Bottom-up Approach), should be used.

TABLE 3.26
DEFAULT IPCC EMISSION PARAMETERS FOR THE FIRE PROTECTION SUB-SOURCE CATEGORY
(BOTTOM-UP APPROACH)

Equipment Type	**Percent of HFCs/PFCs Installed**
Streaming (Portable)	5%
Flooding (Fixed)	5%

Source: HTOC (1998).

CHOICE OF ACTIVITY DATA

Activity data for the top-down method focus on chemical deployment rather than sources of emissions. For the higher tier approach, all of the following types of data are required. If the default emission factor approach is used, only the second type of data is required:

- ***Annual sales and imports of each HFC and PFC to the fire protection industry*****:** Domestic sales data can be obtained from HFC/PFC producers. Customs officials and chemical distributors should be able to provide imported chemical data.
- ***Amount of each HFC and PFC used to charge new fire protection equipment*****:** These data can be estimated using information from fire protection equipment manufacturers/importers on the total charge of the equipment they manufacture/import.
- ***Amount of each HFC and PFC originally used to charge retiring fire protection equipment*****:** Fire protection equipment manufacturers/importers can supply data on average product lifetimes, and the initial charge of retiring equipment. Equipment lifetimes can be long, however, possibly up to 35 years, and ODS substitutes have only recently been introduced to the industry. Consequently, at present, there may be only a minimal amount of HFCs and PFCs contained in retiring equipment.

A top-down model for estimating global halon emissions was developed in 1991, based on the magnitude of the halons contained in equipment and the supply that would be available from recovery and recycle.[61] In the future, a similar model could be developed to determine the share of global HFC/PFC production sold to the fire protection industry, and subsequently this production could be allocated to global regions.[62] Such a model could assist countries experiencing difficulty obtaining national HFC/PFC data for the fire protection industry data.

COMPLETENESS

Inventory agencies should ensure that all HFCs and PFCs used in the fire protection industry are included in the estimate. If chemical sales and imports data are complete, the final estimate should be complete as well.

Aggregate global production will always equal aggregate global emissions plus the aggregate total of ODS substitutes contained in equipment. For inventory agencies that use a global model in the future, estimates will be complete if the global and regional data are allocated accurately.

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[61] The model was published in the 1992 Report of the Halons Technical Options Committee (HTOC) of the Montreal Protocol and widely accepted at that time.

[62] The expert group recommended that the model include ten regions as follows: North America, Europe, Japan, Australia/New Zealand, Indian sub-continent, Northeast Asia, ASEAN, Africa including Turkey, Central and South America, and countries with economies in transition (CEITs).

DEVELOPING A CONSISTENT TIME SERIES

In some countries, historical activity data for HFCs and PFCs charged into new equipment may be difficult to determine because of the recent introduction of these substances. If inventory agencies use preliminary emission factors for these years based on historical data for halons, and then switch to the chemical sales approach, they should follow *good practice* in ensuring time series consistency, as described in Chapter 7, Methodological Choice and Recalculation.

UNCERTAINTY ASSESSMENT

The Tier 2 top-down approach will be more accurate than the simplified emission factor approach because emissions do not correlate well to a fixed percentage of annual production, and an emission factor cannot properly account for emissions from older equipment. The accuracy of the top-down approach will depend on the quality of chemical sales data. It should be possible to estimate annual emissions to ±10% using this method.

A high degree of certainty could be expected for the global model because it will be based on known production and provides for a complete material balance. At any time, Aggregate Global Production will always equal Aggregate Global Emissions plus the Aggregate Total of ODS substitutes Contained in Equipment. There is more uncertainty in the regional and country-specific disaggregation of the data.

3.7.6.2 Reporting and documentation

The balance between preservation of confidentiality and transparency of the data is an important issue, especially in a low use sub-source category such as fire protection. One major ODS substitute is manufactured by only one producer, in quantities very much lower than ODS substitutes used in other sub-source categories. Careful aggregation of GWP-weighted data may be a means to resolve this issue.

3.7.6.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1, General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, Section 8.7, Source Category-specific QC Procedures (Tier 2), and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

In addition to the guidance in Chapter 8, Quality Assurance and Quality Control, specific procedures of relevance to this sub-source category are outlined as follows. The potential for global validation of the quantity of chemicals used and their sources cannot be used to substantiate individual country data. However, quality control can be addressed by emissions cross checks using regional and global data as country data is a subset of these. Agreement on factors, reached by a consensus on a regional and global basis, will maintain the integrity of the overall model.

3.7.7 Other applications sub-source category

3.7.7.1 Methodological issues

HFCs and PFCs represent a large range of gases whose properties make them attractive for a variety of niche applications not covered in other sub-source categories. These include electronics testing, heat transfer, dielectric fluid, medical applications and potentially many new applications not yet developed. There are also some historical uses of PFCs, as well as emerging use of HFCs, in these applications. These applications have leakage rates ranging from 100% emissive in year of application to around 1% per annum.

CHOICE OF METHOD

The choice of *good practice* methods depends on national circumstances (see decision tree in Figure 3.18, Decision Tree for Actual Emissions (Tier 2) from the Other Applications Sub-source Category). The end-users for these niche applications will be extremely diverse. As a result, investigating each of these applications separately may not be feasible. Instead, it is suggested that these other miscellaneous applications be divided into highly emissive applications similar to solvents and aerosols, and less emissive contained applications similar to closed-cell foam and refrigerators. The breakdown of annual gas consumption going to either category should be determined by a survey of end-use applications.

The following default split of usage is suggested:

- Emissive = X% of total consumption
- Contained = (100 – X)% of total consumption

Modelling of these two circumstances are considered in turn.

Emissive applications

It is *good practice* to use a top-down method, similar to the methods described for aerosols and solvents. During use of fluids in these applications, 100% of the chemical is emitted on average six months after sale. In other words, as with aerosol uses, emissions in year t can be calculated according to the equation for solvents and aerosols as follows:

EQUATION 3.53

$$\text{Emissions of HFCs and PFCs in year t} = [\text{Quantity of HFCs and PFCs Sold in year t} \bullet (\text{EF})] + [\text{Quantity of HFCs and PFCs Sold in year (t – 1)} \bullet (1 - \text{EF})]$$

The emission factor (EF) represents that fraction of chemical emitted during the first year of sale. By definition, emissions over two years must equal 100%. This equation should be applied to each chemical individually. Total CO_2-equivalent emissions are equal to the sum of CO_2-equivalent emissions of each chemical.

Contained applications

Certain applications have much lower loss rates. Where bottom-up data are available, a separate emissions model will be required to adjust for this lower leakage rate. Where no data exist, a bottom-up model with default emission factors should be used. Thus, the equation for annual emissions is as follows:

EQUATION 3.54

$$\text{Emissions} = \text{Product Manufacturing Emissions} + \text{Product Life Emissions} + \text{Product Disposal Emissions}$$

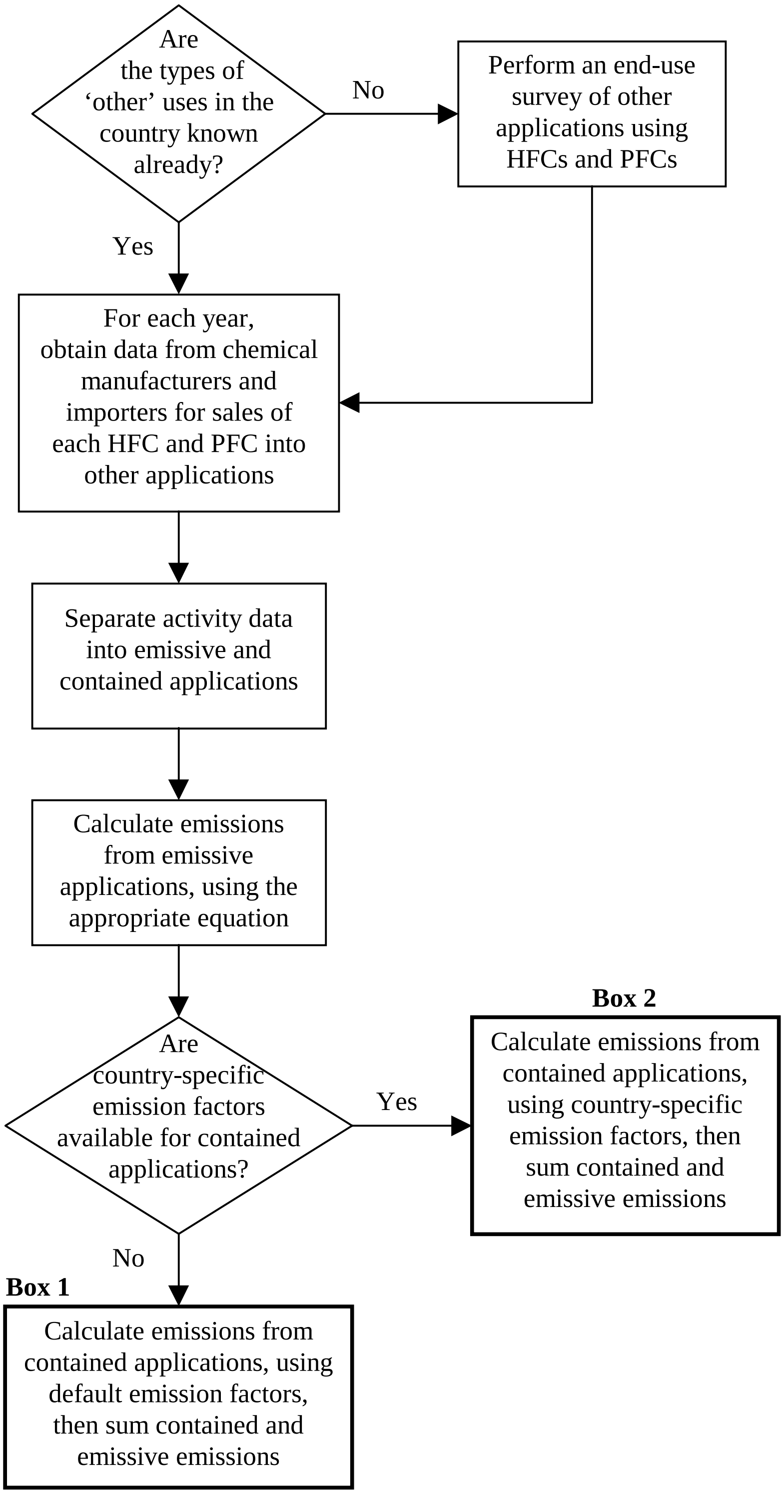
Where:

Product Manufacturing emissions = Annual Sales • Manufacturing Emission Factor

Product Life emissions = Bank • Leakage Rate

Product Disposal emissions = Annual Sales • Disposal Emission Factor

Figure 3.18 Decision Tree for Actual Emissions (Tier 2) from the Other Applications Sub-source Category



CHOICE OF EMISSION FACTORS

Emissive applications

In the absence of empirical end-use data, *good practice* is to use the IPCC default emission factor of 50%. This means that half of the initial charge is emitted during the first year, and the remainder is emitted during the second year. If alternative emission factors are used, they should be fully documented.

Contained applications

The suggested approach is to obtain data directly from the end-use sectors. If it is impossible to obtain such data, default values are presented below in Table 3.27, Default IPCC Emission Parameters for Contained Applications (Other Applications Sub-source Category). These defaults assume a low annual leakage rate and a long equipment life, as should be expected from contained applications.

TABLE 3.27
DEFAULT IPCC EMISSION PARAMETERS FOR CONTAINED APPLICATIONS (OTHER APPLICATIONS SUB-SOURCE CATEGORY)

Emissions Parameter	Default Value
Manufacturing emission factor	1% of Annual Sales
Leakage rate	2% of Annual Sales
Disposal emission factor	5% of Annual Sales
Equipment lifetime	15 years

Source: Gamlen *et al.* (1986).

CHOICE OF ACTIVITY DATA

The value for total sales going to other uses should be obtained directly from chemical HFC/PFC producers and importers. Data on the import of HFCs and PFCs can be collected from distributors. Most countries will import a significant amount of these substances because there are few produced. Data can also be collected from end-users but this will be difficult. The fraction of sales going to emissive uses, as opposed to contained uses, should be determined by a survey of end uses.

For contained applications, it is also necessary to determine the size of the bank of fluid accumulated. The suggested approach is to use data directly from end-use sub-source categories to determine the size of the bank. If it is impossible to obtain such data, it is *good practice* to use a default value of 10 times annual sales. Thus, annual emissions including manufacturing losses and disposal will average 26% of annual chemical sales to contained applications, compared to the emissive applications where 100% of annual sales is lost.

COMPLETENESS

Completeness will be difficult to achieve because there is no fixed list of other sources. Inventory agencies should investigate possible end-uses by obtaining qualitative information from chemical manufacturers and importers about other industries that purchase HFCs and PFCs.

DEVELOPING A CONSISTENT TIME SERIES

Emissions of ODS substitutes from other applications should be calculated using the same method and data sources for every year in the time series. Where consistent data are unavailable for any years in the time series, these gaps should be recalculated according to the guidance provided in Chapter 7, Methodological Choice and Recalculation.

UNCERTAINTY ASSESSMENT

As there are a small number of chemical manufacturers, and the high cost of the gas provides an incentive for keeping records, the activity data should be reasonably accurate. There is more uncertainty in determining the breakdown between emissive and contained applications, particularly when no end-use survey is performed. For emissive applications, the default emission factor of 50%/yr applied over two years will be most accurate if gas sales are relatively constant. Emissions factors for contained applications have a higher uncertainty, although data from end-use sectors is likely to be more accurate than defaults. It is *good practice* to discuss uncertainty estimates with the chemical supplier and end user sectors concerned, using the approaches to obtaining expert judgement outlined in Chapter 6, Quantifying Uncertainties in Practice.

3.7.7.2 Reporting and documentation

Inventory agencies should report total emissions from these other sub-source categories, and qualitatively list the types of uses included in this sub-source category if available. The fraction of chemical used in emissive versus contained applications should also be reported, along with any country-specific emission factors. There may be confidentiality issues due to the limited number and location of chemical manufacturers that will affect the level of transparency. In this case, to preserve confidentiality, it may be necessary to avoid specifying emissions of individual gases, and reports should be as aggregated tonnes of carbon equivalent emissions, weighted by global warming potential.

3.7.7.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, Section 8.7, Source Category-specific QC Procedures (Tier 2), and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

In addition to the guidance in Chapter 8, Quality Assurance and Quality Control, specific procedures of relevance to this sub-source category are outlined as follows:

- For accurate quality control/assurance it is suggested that both top-down and end-use data be compiled.
- To allow independent assessment of the level of quality of the data and underlying assumptions, the number of manufacturers and distributors plus end users interviewed should be quantified.

3.8 ESTIMATION OF HFC-23 EMISSIONS FROM HCFC-22 MANUFACTURE

3.8.1 Methodological issues

Trifluoromethane (HFC-23 or CHF_3) is generated as a by-product during the manufacture of chlorodifluoromethane (HCFC-22 or $CHClF_2$)[63] and emitted through the plant condenser vent. There are a small number of HCFC-22 production plants globally and thus a discreet number of point sources of HFC-23 emissions.

CHOICE OF METHOD

The choice of *good practice* method will depend on national circumstances. The decision tree in Figure 3.19, Decision Tree for HFC-23 Emissions from HCFC-22 Production, describes *good practice* in adapting the methods in the *IPCC Guidelines* to these country-specific circumstances.

The *IPCC Guidelines* (Vol. 3, Section 2.16.1, By-product Emissions) present two broad approaches to estimating HFC-23 emissions from HCFC-22 plants. The Tier 2 method is based on measurement of the concentration and flow-rate from the condenser vent at individual plants. The product of HFC-23 concentration multiplied by the volumetric flow-rate gives the mass rate of HFC-23 emissions. The Tier 1 method is relatively simple, involving the application of a default emissions factor to the quantity of HCFC-22 produced. This method can be applied at the plant level or the national level. In cases where there are Tier 2 data available for some plants, the Tier 1 method can be applied to the remainder to ensure complete coverage. Regardless of the method, emissions abated should be subtracted from the gross estimate to determine net emissions.

It is *good practice* to use the Tier 2 method if possible. Direct measurement is significantly more accurate than Tier 1 because it reflects the conditions specific to each manufacturing facility. In most cases, the data necessary to prepare Tier 2 estimates should be available because facilities operating to good business practice perform regular or periodic sampling of the final process vent or within the process itself as part of routine operations. For facilities using abatement techniques such as HFC-23 destruction, verification of the abatement efficiency is also done routinely. The Tier 1 method should be used only in rare cases where plant-specific data are unavailable.

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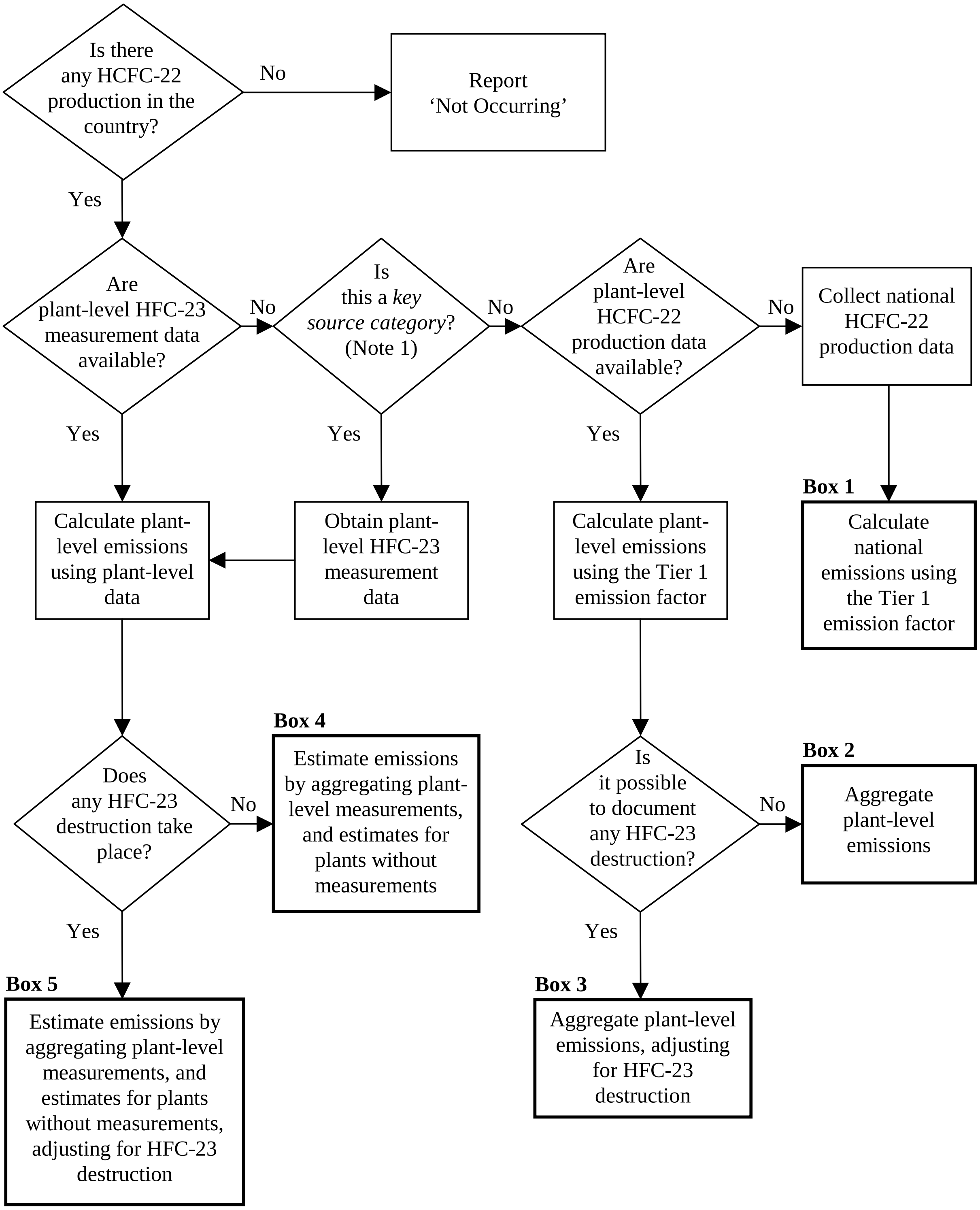
[63] HCFC-22 is used as a refrigerant in several different applications, as a blend component in foam blowing, and as a chemical feedstock for manufacturing synthetic polymers.

Figure 3.19 Decision Tree for HFC-23 Emissions from HCFC-22 Production



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

CHOICE OF EMISSION FACTORS

There are several measurement options within the Tier 2 method relating to the location and frequency of the sampling. In general, direct measurement of the emissions of HFC-23 provides the highest accuracy. Continuous or frequent measurement of parameters within the production process area itself is almost as accurate. In both cases, the frequency of measurement must be high enough to represent the variability in the process (e.g. across the life of the catalyst). Issues related to measurement frequency are summarised in Box 3.5, Plant Measurement Frequency. General advice on sampling and representativeness is provided in Chapter 8, Quality Assurance and Quality Control. In cases where plant-specific measurements or sampling are not available and Tier 1 methods are used, the default emission factor of 4% (tonnes of HFC-23 produced per tonne of HCFC-22 manufactured) presented in the *IPCC Guidelines* should be used, assuming no abatement methods.

BOX 3.5

PLANT MEASUREMENT FREQUENCY

The accuracy and precision of the estimates of annual HFC-23 emissions are directly correlated with the number of samples and the frequency of sample collection. Since production processes are not completely static, the greater the process variability, the more frequently plants need to measure. As a general rule, sampling and analysis should be repeated whenever a plant makes any significant process changes. Before choosing a sampling frequency, the plant should set a goal for accuracy and use statistical tools to determine the sample size necessary to achieve the goal. For example, a study of HCFC-22 producers indicates that sampling once per day is sufficient to achieve an extremely accurate annual estimate. This accuracy goal should then be revised, if necessary, to take into account the available resources.

RTI, Cadmus, '*Performance Standards for Determining Emissions of HFC-23 from the Production of HCFC-22*', *draft final report* prepared for USEPA, February 1998.

CHOICE OF ACTIVITY DATA

When using the Tier 1 method, production data should be obtained directly from producers. There are several ways producers may determine their production levels, including shipment weights and measuring volume-times-density, using flow meters. These data should account for all HCFC-22 production for the year, whether for sale or for use internally as feedstock, and the plant should describe how the HCFC-22 production rate is determined. In some circumstances, producers may consider plant production data to be confidential. For national-level activity data, submission of HCFC-22 production data is already required under the Montreal Protocol.

COMPLETENESS

It should be possible to obtain complete sampling data because there are only a small number of HCFC-22 plants in each country, and it is standard practice for each plant operator to monitor emissions. Review of plant data indicates that at properly run manufacturing facilities, fugitive emissions of HFC-23 (e.g. from valves, water scrubbers, and caustic washes) are insignificant (RTI, 1996). If information is available that indicates fugitive emissions are significant, they should be reported and well documented.

DEVELOPING A CONSISTENT TIME SERIES

Emission of HFC-23 from HCFC-22 production should be estimated using the same method for the entire time series. If data for any years in the time series are unavailable for the Tier 2 method, these gaps should be filled according to the guidance provided in Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques.

UNCERTAINTY ASSESSMENT

The Tier 2 method is significantly more accurate than the Tier 1 default method. An error of approximately 50% could be considered for Tier 1 method based upon knowledge of the variability in emissions from different manufacturing facilities. Regular Tier 2 sampling of the vent stream can achieve an accuracy of 1-2% at a 95% confidence level in HFC-23 emissions. Tier 1 uncertainties can be identified through expert judgement whereas Tier 2 uncertainties should be based on empirical measurement.

3.8.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving.

Some examples of specific documentation and reporting relevant to this source category are provided below:

- To provide for completely transparent reporting, emissions of HFC-23 from HCFC-22 production should be reported as a separate item, rather than included with other HFC emissions.
- Documentation should also include:
  - (i) Methodological description;
  - (ii) Number of HCFC-22 plants;
  - (iii) HCFC-22 production (if multiple producers);
  - (iv) Presence of abatement technology;
  - (v) Emission factors.

Confidentiality

- The use of the Tier 2 method would mean that the plant emissions of HFC-23 are reported separately from the production of HCFC-22. By de-coupling the HFC-23 emissions and HCFC-22 production, the emission data on HFC-23 cannot be considered to be of commercial confidence as it does not reveal the levels of production of HCFC-22 without detailed and confidential knowledge of the individual manufacturing facility.
- The use of the Tier 1 method would enable the production of HCFC-22 to be calculated from published emissions of HFC-23 if there were less than three producers. Such production data could be considered confidential business information for the manufacturing facility concerned. In such cases, steps should be taken to protect confidentiality through, for example, the aggregation of all HFC emissions. For transparency reasons, whenever there is aggregation, a qualitative discussion of HCFC-22 production should be included.

3.8.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, Section 8.7, Source Category-specific QC Procedures (Tier 2), and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

In addition to the guidance in Chapter 8, Quality Assurance and Quality Control, specific procedures of relevance to this sub-source category are outlined below:

Comparison of emissions estimates using different approaches

Inventory agencies should compare reported plant emissions estimates against those determined using the Tier 1 default factor and production data. If only national production data are available, they should compare aggregated plant emissions to a national default estimate. If significant differences are found in the comparison, they should answer the following questions:

- (i) Are there inaccuracies associated with any of the individual plant estimates (e.g. an extreme outlier may be accounting for an unreasonable quantity of emissions)?
- (ii) Are the plant-specific emission factors significantly different from one another?
- (iii) Are the plant-specific production rates consistent with published national level production rates?
- (iv) Is there any other explanation for a significant difference, such as the effect of controls, the manner in which production is reported or possibly undocumented assumptions?

Direct emission measurement check

- Inventory agencies should confirm that internationally recognised, standard methods were used for plant measurements. If the measurement practices fail this criterion, then the use of these emissions data should be carefully evaluated. It is also possible that, where a high standard of measurement and QA/QC is in place at sites, the uncertainty of the emissions estimates may be revised downwards.
- Each plant's QA/QC process should be evaluated to assess if the number of samples and the frequency of sample collection is appropriate given the variability in the process itself.
- Where possible, inventory agencies should verify all measured and calculated data through comparison with other systems of measurement or calculation. For example, emissions measurement within the process itself can be verified periodically with measurement of the vent stream. Inventory agencies should verify abatement system utilisation and efficiency.
- With a periodic external audit of the plant measurement techniques and results, it is also possible to compare implied emission factors across plants and account for major differences.

Verification of national emissions

- While it is not feasible to verify a single country's estimate, an overall global cross-check of estimated emissions could be carried out through the measurement of HFC-23 atmospheric levels. As there are a small number of facilities, this will serve as an order-of-magnitude check for emissions from the industry world-wide that in turn may be compared to national estimates.

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