CHAPTER 6

ELECTRONICS INDUSTRY EMISSIONS

Authors

Laurie Beu (USA) and Sebastien Raoux (France/USA)

Yun Chung (Jack) Chang (USA), Michael Roger Czerniak (UK), Francesca Illuzzi (Italy), Tetsuya Kitagawa (Japan), Deborah Ottinger (USA) and Natalya Parasyuk (Ukraine)

Contributing Authors

Stephanie N. Bogle (USA), Shoumian Chen (China), Joseph Van Gompel (USA), Melissa Ann Gresham (USA), David Harman (USA), Kyungah Kim (Republic of Korea), Joey (Ching-Hui) Lu (Taiwan, Province of China), Youngsook Lyu (Republic of Korea), Brian K. Raley (USA) and Jennifer Politsch (USA)

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Users are expected to go to the Mapping Tables in Annex 5, before reading this chapter. This is required to correctly understand both the refinements made and how the elements in this chapter relate to the corresponding chapter in the 2006 IPCC Guidelines.

This Chapter 6 Volume 3 of the *2019 Refinement* is a complete update of Chapter 6 Volume 3 of the *2006 IPCC Guidelines* and should be used instead of Chapter 6 Volume 3 of the *2006 IPCC Guidelines*.

The *2019 Refinement* of Volume 3 Chapter 6 was designed to maintain the scientific validity of GHG emissions estimates from the electronics industry. Compared to the *2006 IPCC Guidelines*, the *2019 Refinement* takes into account the changes in manufacturing processes and equipment that have occurred in the electronics industry during the thirteen-year interim period and reflect the much larger set of experimental data available (as of 2018 compared to 2006) to calculate default emissions factors for the sector. Also, several methodological refinements are introduced in an attempt to increase accuracy and flexibility, depending on how reporting facilities track gas usage and implement emissions control technologies. The *2019 Refinement* includes six revised methods (Tier 1, 2a, 2b, 2c, 3a, and 3b), compared to four for the *2006 IPCC Guidelines*. Section 6.1.2 and the mapping Tables in Annex 5 summarize the substantial refinements of this Chapter. Annex 5 provides a list of the sections, equations, tables, figures, and boxes that have been refined in this chapter, describing the type of refinement and a comparison between the *2006 IPCC Guidelines* and the *2019 Refinement*.

6.1 INTRODUCTION

6.1.1 Overview of emissions and their sources

As part of its manufacturing processes, the electronics industry uses and emits greenhouse gases (GHGs) from the family of fluorinated compounds (FCs) and nitrous oxide (N_2O). The specific electronic industry sub-sectors discussed in this chapter include the manufacturing of semiconductor devices, microelectromechanical systems (MEMS), photovoltaic (PV) devices, and displays, which in turn consist of thin-film-transistors (TFTs) for displays and organic light emitting diodes (OLEDs). FC emissions from waterproofing of electronic circuits are discussed in Chapter 8 of this Volume.

The electronics industry currently emits both FCs that are gases at room temperature (FC gases) and fluorinated compounds that are liquids at room temperature (fluorinated liquids) and that enter the atmosphere through evaporation. FC gases are used in two important steps of electronics manufacturing: (i) plasma etching and wafer cleaning (EWC) of silicon-containing materials and (ii) cleaning of the chamber walls of thin-film deposition (TFD) and diffusion tools after processing substrates. Electronic manufacturers also use fluorinated liquids as heat transfer fluids (HTFs) for temperature control during certain processes, as well as during testing of packaged semiconductor devices and during vapour phase reflow soldering of electronic components to circuit boards. In addition, fluorinated liquids are sometimes used to clean substrate surfaces, e.g., for MEMS. (Before 2010, fluorinated liquids were occasionally used to clean TFT-display panels during manufacture, but this is no longer believed to be the case.) Finally, electronics manufacturers use N_2O as an input gas during TFD processes and for other N_2O-using manufacturing processes such as diffusion and dry removal of photoresist.

For the purpose of this Chapter, FC gases are defined to include perfluoromethane (CF_4), perfluoroethane C_2F_6, perfluoropropane (C_3F_8), 1,3-hexafluorobutadiene (C_4F_6), perfluorocyclobutane (c-C_4F_8), octafluorotetrahydrofuran (C_4F_8O), octafluorocyclopentene (c-C_5F_8), trifluoromethane (CHF_3), difluoromethane (CH_2F_2), fluoromethane (CH_3F), pentafluoroethane (C_2HF_5), nitrogen trifluoride (NF_3), and sulphur hexafluoride (SF_6). Although not considered to be greenhouse gases, carbonyl fluoride (COF_2), and fluorine (F_2) should be tracked as input gases because they are known to create FC gas by-products which should be included in the inventory. Fluorinated liquid emissions consist primarily of hydrofluoroethers, perfluoropolyethers (including PFPMIE), and other fully fluorinated liquids (perfluorinated amines and perfluoroalkylmorpholines). More than 40 different fluorinated liquids are marketed to the electronics industry, often as mixtures of fully fluorinated compounds. Although this list of FC gases and classes of fluorinated liquids is believed to include all relevant compounds used in appreciable quantities for the production of electronic devices as of this writing, FC gases and fluorinated liquids that should be considered for inventory purposes under this Chapter could also include other fluorinated compounds currently used in small quantities for production or for research and development (R&D) purposes, and FC gases and fluorinated liquids that may be used in the future for manufacturing electronic devices. In general, fluorinated compounds that are greenhouse gases or whose use during the manufacturing of electronic devices could result in emissions of greenhouse gases should be considered.

Both plasma etching and wafer and thin film deposition (TFD) chamber cleaning processes use plasma or thermal energy to break down fluorinated compounds into fluorine atoms and other reactive species to perform these process steps. TFD and other N_2O-using processes also use plasma or thermal energy to break down N_2O molecules and generate oxygen or nitrogen atoms or molecules and other excited species to perform the process. The majority of FC gases and N_2O emissions result from the failure to completely break down the FC gases or N_2O molecules that are fed into the process, causing the utilisation efficiency of the input gases to be limited. In addition, a fraction of FC input gases used in the production process can be converted into FC gas by-products such as CF_4, C_2F_6, C_4F_6, C_4F_8, C_3F_8, CHF_3, CH_2F_2, and CH_3F. Several of these by-products can also be formed even if no carbon-containing FCs are fed into the process. In particular, processes using molecular fluorine (F_2), nitrogen trifluoride (NF_3), sulphur hexafluoride (SF_6), or chlorine trifluoride (ClF_3) input gases can generate CF_4, C_2F_6, CHF_3, CH_2F_2, CH_3F (and potentially other FC gases) as by-products of etching carbon-containing materials or cleaning chambers previously used to deposit carbon-containing thin films.[1] Moreover, under certain circumstances, CF_4 may be formed in combustion-based emissions control systems using hydrocarbon fuels by reaction between the fuel and fluorinated species (e.g. F_2) emitted during F_2 and remote NF_3 chamber cleans; thus, an appropriate CF_4 by-product emission factor ($AB_{i,CF4}$) should be used to account for this phenomenon. Finally, with respect to fluorinated liquids, emissions occur through evaporative losses. Table 6.1 summarizes the sources and types of GHGs emitted during electronics manufacturing and identifies the section of this Refinement where they are discussed.

TABLE 6.1 (NEW)
SOURCES AND TYPES OF GHGS EMITTED DURING ELECTRONICS MANUFACTURING

Source	**GHG(s) Emitted**	**Relevant Sections of Volume 3 of *2019 Refinement***
Incompletely utilized FC gases fed into plasma etching, wafer cleaning, and chamber cleaning processes	Multiple FC gases	6.2.1.1, 6.2.2.1
By-products formed from carbon-containing FC gases fed into plasma etching, wafer cleaning, and chamber cleaning processes	Multiple FC gases	6.2.1.1 (See especially Box 6.2), 6.2.2.1
By-products formed from fluorine-containing gases (e.g., NF_3, F_2, COF_2) fed into plasma etching, wafer, cleaning, and chamber cleaning processes that involve carbon-containing films	Multiple FC gases	6.2.1.1 (See especially Box 6.2 and discussion following Equation 6.6), 6.2.2.1
By-product formed in some combustion-based FC emissions control systems	CF_4	6.2.1.1 (Equation 6.7 for Tiers 2a and 2b, Equation 6.15 for Tiers 2c and 3a)
Incompletely utilized N_2O fed into thin film deposition and other (e.g., diffusion) processes	N_2O	6.2.1.1 (throughout)
Fluorinated liquids used for temperature control, device testing, cleaning substrate surfaces and other parts, and soldering	Multiple FC liquids	6.2.1.2, 6.2.2.2, (See especially Table 6.5)
FCs emitted during waterproofing of electronic circuits	Multiple FC gases	Chapter 8, section 8.3 (See discussion near Equation 8.22A)

6.1.2 Summary of refinements

The Tier 1 method of the *2019 Refinement* uses the same approach as in the *2006 IPCC Guidelines*, where emissions are estimated based on the surface area of substrate produced for each sub-sector, but the Tier 1 default emissions factors (EFs) for semiconductor and display manufacturing have been updated to account for technological advancements and for the use of a broader basket of FC gases and fluorinated liquids. In addition, default EFs for MEMS have been introduced.

The Tier 2 and 3 methods of the *2019 Refinement*, like their predecessors in the *2006 IPCC Guidelines*, are based on gas consumption. The 2006 Tier 2a method is updated as a new refined 2019 Tier 2a method for the

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[1] When using cleaning or etching gases that do not contain carbon (e.g. F_2, NF_3, SF_6, or ClF_3), CF_4 and other FCs with high GWPs can be formed during the etching or cleaning of carbon-containing thin films, thus resulting in global warming emissions from the process. In particular, it should be noted that emissions of CF_4 and other FC by-products with high GWPs should be taken into account, even when the cleaning or etching precursor itself has no or low global warming potential (such as F_2, COF_2, or ClF_3). Please see section 6.2.2.1 for more detail.

semiconductor sub-sector with revised emission factors, also accounting for additional precursors and by-products. For the display sub-sector, the *2019 Refinement* no longer provides a Tier 2a method because it is typically not needed. For the PV sub-sector, the 2006 Tier 2a method default factors cannot be applied to the 2019 Tier 2a method.

The 2006 Tier 2b method, which formerly distinguished emission factors by process types (etch versus chemical vapour deposition (CVD)[2] chamber clean) is now replaced with a new refined 2019 Tier 2b method using emission factors applicable to different wafer sizes for the semiconductor sub-sector (≤200 mm or 300 mm). Note that the revised 2019 Tier 2b method no longer distinguishes EFs by process types (this is now done under the new 2019 Tier 2c method), and that the 2019 Tier 2b method is applicable only to the semiconductor sub-sector.

The new 2019 Tier 2c method for the semiconductor sub-sector distinguishes emissions factors by both wafer size (≤200 mm or 300 mm), and by refined process types. For the display and PV sub-sectors, the Tier 2c method does not distinguish by substrate size but provides differentiated emission factors by process types.

Using the Tier 2 and Tier 3a methods requires some degree of apportioning of gas consumption. That is, the consumption of input gases should be differentiated by process type (e.g. etching vs. chamber cleaning). Compared to the *2006 IPCC Guidelines*, the *2019 Refinement* provides additional guidance to apportion gas consumption to different process types.

The 2006 Tier 3 method, which was based on process-specific parameters has evolved into a new 2019 Tier 3a method, which provides increased guidance for estimating emissions using measured, site-specific emissions factors (as opposed to the default emission factors used for the Tier 2 methods). In principle, the Tier 3a method is applicable to all sub-sectors (semiconductor, display, MEMS, PV).

The *2019 Refinement* includes a new ‘stack’ Tier 3b method to develop site-specific emission factors based on measurements at the stack level. Like the Tier 3a method, the 3b method is applicable to all sub-sectors.

Finally, it should be noted that, in addition to emissions arising from the direct manufacture of semiconductor, display, MEMS, and PV devices themselves, account has also been taken in the *2019 Refinement* for GHG emissions (including a variety of FC gases) from the application of thin, conformal waterproofing films to assembled circuit boards as used in electronic devices that are likely to be exposed to the weather; a good example being mobile (“cellular” or “smart”) phones. This is discussed separately in Chapter 8 of the *2019 Refinement*.

Table 6.2 summarizes the refinements and applicability of each Tier by electronics industry sub-sector.

TABLE 6.2 (NEW)
REFINEMENTS AND APPLICABILITY OF GUIDANCE BY ELECTRONICS INDUSTRY SUBSECTOR

Electronics Industry Subsector	**Gaseous Fluorinated compounds and N_2O**						**Fluorinated Liquids**	
	Tier 1	**Tier 2a**	**Tier 2b**	**Tier 2c**	**Tier 3a**	**Tier 3b**	**Tier 1**	**Tier 2**
Semiconductors	U	U	U	NG	U	NG	U	NR
Display (formerly “FPD” or “LCD”)	U	*NA*	*NA*	U[1]	U	NG	U	NR
Photovoltaic	NR	*NA*	*NA*	U[2]	U	NG	U	NR
MEMS	NG	*NA*[3]	*NA*[3]	*NA*[3]	U	NG	U	NR

U – Update, NG – New Guidance, NR – No Refinement, *NA* – Not Applicable

[1] For display, the Tier 2c method updates the default emission factors for the *2006 IPCC Guidelines* Tier 2b method but is otherwise similar to the former 2b method. The Tier 2c method does not distinguish by substrate size for display.

[2] While the Tier 2 methods for all electronics sub-sectors were updated (e.g., to include additional guidance on gas apportioning and abatement), the default Tier 2c emission factors for photovoltaic manufacturing were not updated and are the same as for the *2006 IPCC Guidelines* Tier 2b method.

[3] Data were not available to calculate separate Tier 2 default EFs for MEMS manufacturing, but the corresponding Tier 2 EFs for semiconductors may be applied to MEMS manufacturing that uses semiconductor manufacturing tools.

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[2] This chapter uses the term “thin-film deposition,” which encompasses chemical vapour deposition as well as other thin film deposition techniques.

6.2 METHODOLOGICAL ISSUES

6.2.1 Choice of method

6.2.1.1 GASEOUS FLUORINATED COMPOUNDS AND NITROUS OXIDE

Emissions of gaseous fluorinated compounds (FCs) and nitrous oxide from electronics manufacturing vary according to the quantities of the gases used (which vary roughly with the quantity of substrate processed), the identities of the gases used, the processes used, the wafer size (for semiconductors), and the type and implementation of emissions control technologies. The choice of methods will depend on data availability and whether the electronics source category is *key*. See Figure 6.1 (Decision tree for estimation of GHG emissions from electronics manufacturing) and Tables 6.3 and 6.4 (Information for sources necessary for completing the tiered emissions estimating methods for electronics manufacturing) for more information.

Continuous (in-situ) emissions monitoring is not currently considered an economically viable means to estimate emissions from the electronics industry; however, greenhouse gas emissions are periodically measured at the process tool exhaust during the development of new processes and tools, generally for centreline process conditions.[3] Such measurements, performed on a large set of processes and averaged at varying levels of aggregation, form the basis of the Tier 1 and Tier 2 default emission factors presented in this guidance. They can also be performed by individual facilities and/or their tool suppliers to develop emission factors for specific process recipes or families of recipes when using the Tier 3a method. Finally, some facilities may periodically (for short periods of time) install equipment to measure emissions from their stacks for purposes of developing facility-specific emission factors to estimate emissions over the long term, as required by the Tier 3b method.

As discussed further below, the precision of the emissions estimate generally improves as one moves from lower to higher Tiers, accounting for more and more site-specific factors. For any single facility, the accuracy of the methods depends, among other things, on the differences between the emission factors of the processes actually used in production and the emission factors of a particular method, and on potential errors in calculating the overall efficiency and uptime of emissions control equipment. These differences and errors are likely to decrease (though not to disappear) as the Tier is increased. Errors in gas consumption measurements and apportioning can also occur and can limit the improvement in precision achieved by characterizing processes at a highly detailed level (e.g., in the Tier 3a method). However, apportioning errors depend on the measurements or model used and, if the guidance provided below is followed, are not expected to become important at the Tier 2 level (e.g., in moving from Tier 2a to Tier 2c). Thus, the use of higher tiered methods is strongly encouraged, especially in the case where default emission factors do not exist.

Where no gas consumption data is available and the electronics category is not *key*, emissions can be estimated using the Tier 1 method based on production figures (surface area of substrate used during the production of electronic devices). However, this approach is the least accurate and should be used only in cases where company-specific gas consumption data is not available. The uncertainty of the Tier 1 method is very high because it does not account for the quantities of the gases consumed (which are only loosely correlated with production), the identities of the gases consumed, the process type, the wafer size (for semiconductors), or the use of emissions control technology.

The Tier 2 methods are expected to be more accurate than the Tier 1 method because they rely on the actual consumption of individual gases and account for the use of emissions control technology. To varying extents, they also distinguish among process types and, for semiconductor manufacturing, wafer sizes. Note that insufficient data was available to calculate Tier 2 factors specifically for MEMS manufacturing; however, the corresponding semiconductor Tier 2 emission factors may be applied unless the MEMS are manufactured using MEMS-specific processes and manufacturing tools. If MEMS-specific manufacturing tools are used, the only higher-Tiered methods available are the Tier 3a and 3b methods.

The Tier 2a method does not distinguish among process types for most GHGs. The exceptions are NF_3 and C_3F_8, for which the Tier 2a method distinguishes between two process types (remote plasma clean vs. all other processes), and N_2O, for which the Tier 2a method distinguishes between two process types for semiconductor manufacturing

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[3] Centreline conditions refer to specific process conditions of gas flows, chamber pressure, processing time, plasma power, etc., for which an electronic device manufacturer may have measured emissions, or specific process conditions that may have been provided by a tool manufacturer who standardized its equipment for sale. Note that it is common for electronic devices manufacturers to modify centreline process conditions (developed in-house or by tool manufacturers) to optimise for particular needs or for a particular product.

(TFD and "other"). In addition, the 2a method does not distinguish between wafer sizes for semiconductor or MEMS manufacturing. Because emission factors for semiconductor manufacturing vary significantly based on wafer size, the Tier 2a method should only be used in the case of semiconductor facilities processing multiple substrate sizes where it is not possible to distinguish (apportion) gas consumption between the different substrate sizes. The *2019 Refinement* does not provide a Tier 2a method for the display sub-sector because display manufacturers typically use separate gas supplies for different process types, thus enabling the direct use of the more accurate Tier 2c method without having to apportion gas usage.[4] For the PV sub-sector, it should be noted that the 2006 Tier 2a default factors cannot be applied to the 2019 Tier 2a method because no data was available to calculate default γ_i and γ_k values for PV manufacturing. Thus, for PV manufacturing, only the 2019 Tier 2c or the 2019 Tier 3 methods are available.

The 2b method applies only to semiconductor manufacturing and to MEMS manufacturing that uses tools and processes which are similar to those used to manufacture semiconductors. The Tier 2b method is identical to the 2a method except that it provides emission factors that depend on the size of the wafers used for manufacturing ($\leq$200 mm or 300 mm). The Tier 2b method is therefore more accurate than the Tier 2a method for semiconductor and MEMS manufacturing, and it should be used instead of the Tier 2a method when a facility only has one wafer size.

The Tier 2c method is expected to provide more accurate emission estimates than either of the other Tier 2 methods because it distinguishes among all process types for all GHGs, and it also distinguishes between wafer sizes in the semiconductor sub-sector. In addition, the method provides more accurate estimates of the quantities of FCs exhausted from tools which are connected to emission control systems (see discussion on the γ_i and γ_k factors and on the calculation of a_i and a_k in the next paragraph as well as in the Tier 2a method section, particularly Box 6.3). The Tier 2c method is the only Tier 2 method available for the display and PV sub-sectors. Note that the definitions of process types are specific to each sub-sector: there are 6 distinct process types for the semiconductor sub-sector, 4 process types for the display sub-sector, and 2 process types for the PV sub-sector (see Tier 3a method description for details).

Apportioning is required to track gas consumption to process types and to the sets of tools within each process type that are either abated or unabated. The Tier 2a and 2b methods require only limited apportioning. They are therefore simpler to use than the Tier 2c method, which requires apportioning of all gases to all process types that use those gases. However, the limited apportioning of the Tier 2a and Tier 2b methods significantly increases the uncertainty of their results. Instead of using facility-specific values as the Tier 2c and Tier 3a methods do, the Tier 2a and Tier 2b methods rely on industry average values for (1) the allocation of consumption of each gas to each process type, and (2) in the case of emissions control calculations, the per-tool emissions of each gas from each process type. These averages are respectively embodied in (1) weighted average emission factors for the process gases and (2) default weighting factors (γ_i and γ_k) to account for average per-tool emissions from EWC vs. TFD tools for purposes of calculating the impacts of emissions control systems (D_i and D_k). (All of these quantities are discussed further below.) To the extent that the gas consumption patterns at individual facilities depart from these averages, the Tier 2a and Tier 2b methods will be inaccurate for those facilities. There is potential for large errors because emission factors can vary widely among process types, and the shares of each gas flowing to different process types (as well as per-tool emissions for different process types) vary widely among facilities. For these reasons, the Tier 2a and 2b methods should only be used when it is not possible to distinguish (apportion) gas consumption among the larger number of process types identified in the Tier 2c method.

The methods believed to provide the most accurate and least uncertain estimates of greenhouse gas emissions for electronic devices manufacturing are the Tier 3a and Tier 3b methods.

The Tier 3a method uses the same equations as the Tier 2c method. However, instead of using default emission factors for relatively broad process types, the Tier 3a method uses, at least in part, measured facility-specific emission factors. This enables the Tier 3a method to capture the variability in emission factors that can occur across processes within the same process type, using the same FC gas, and (for semiconductors) occurring on the same wafer size.[5] In theory, the Tier 3a method could be used to assign an emission factor to each centreline

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[4] In the case display manufacturers use the same gas supply containers for multiple process types, a gas consumption apportioning model should be used.

[5] Emission factors for input gas utilisation efficiencies and by-product formation rates can be strongly affected by changes in process variables other than FC gas, substrate size, and process type; these include film and tool type, combination of gases, as well as process recipes variables such as pressure, flow, temperature and plasma power. Further, emission factors for a recipe 'tuned' for a particular purpose or product can differ from those of the centreline process recipe that may have been used for measuring emissions (see Footnote 2). Emission factors can also be affected by the design of the process reactors and can substantially fluctuate from one tool manufacturer to another, even when the process function is similar (e.g. deposition of un-doped silicon dioxide using N_2O, cleaning a TFD reactor after deposition of silicon nitride using NF_3, etching of a trench in an interconnect structure using C_4F_6, etc.).

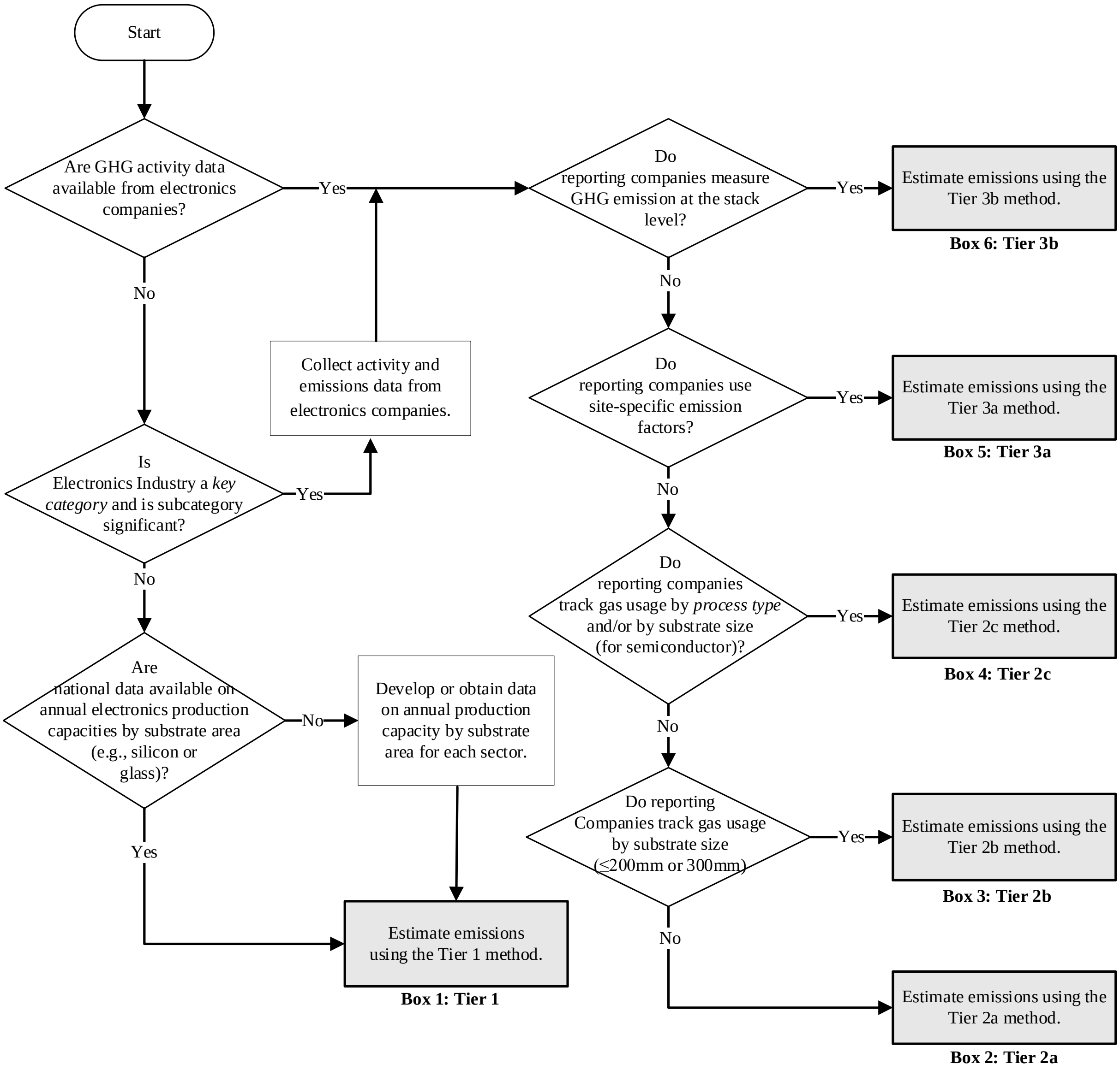
process, recipe, or families of similar recipes (see footnotes 2 and 5 and Tier 3a method discussion), or to assign a specific destruction removal efficiency (DRE) to a particular gas or by-product and emissions control system. It should be noted however that the new Tier 3a method provides more flexibility than the 2006 Tier 3 method in that using it does not require a complete set of measured values (see discussion on the use of 'hybrid' methods in the section on Adapting Tier 2 Methods to Account for Technological Changes). In the case of the Tier 3b method, reporting companies estimate their emissions based on fab-specific emission factors. These emission factors are developed through periodic measurements of stack emissions correlated to 1) the consumption of input gases by the production tools connected to the stack system, and 2) the efficacy of the emissions control technologies used with those tools.

Because the new Tier 3b method is based on the measurement of emissions at the end-of-pipe (stack) level, it can be characterized as a 'top-down' method and contrasted to the Tier 2 and Tier 3a methods, which provide a 'bottom-up' approach by estimating emissions based on consumption at the inlet of the process tools. Thus, comparing the results of the various Tier 2 or Tier 3a bottom-up methods to the new top-down Tier 3b method could provide a measure of the accuracy (or inaccuracy) of the methods.

With respect to accounting for emissions control technologies, it should be noted that the *2019 Refinement* includes significant updates to the guidance on how to account for the use of emission control systems. One significant update is the consideration of the uptime of emissions control systems. Another update is guidance to determine the suitability of using particular emissions control technologies (e.g., cartridge, catalyst, hot-wet, plasma, combustion, new technology) for specific gases. Further, an applicability condition for using default DRE values (Tier 2 and Tier 3 methods) is to obtain a certification by the emissions control system manufacturers that their emissions control systems are capable of removing a particular gas to at least the default DRE in the worst-case flow conditions, as defined by each reporting site. This is important because the efficacy of greenhouse gas emissions control equipment depends on whether it is designed to abate the target gas and on whether it is operated and maintained according to the manufacturer's specifications, especially as regards to not exceeding the individual process gas and total gas flow rates (including any added purge gases) as stated by the emissions control equipment supplier. Guidance is also provided for using site-specific (measured) destruction removal efficiencies to claim DREs that may be different than the default values.

Finally, it should be noted that, even though the logic depicted in Figure 6.1 does not show the possibility of combining tiers, such an approach can be used to improve the accuracy of emissions estimates. If default emission factors are not available under Tier 2 (e.g. if a new wafer size or process type is introduced), or when a default emission factor is known to substantially differ from a facility-specific emission factor, inventory compilers can undertake process emissions characterization under Tier 3a and measure (1-U) and B factors for those new processes without defaults (or with an emission factor different than the default) while using Tier 2 defaults for existing processes (hybrid approach). Similarly, the Tier 2c method might be used for a particular sub-section of a facility and then combined with the Tier 3b method to estimate emissions from another sub-section of a facility, where emissions estimates would be based on measured (stack) emission factors. However, reporting companies should not combine the Tier 1 method with any other method.

Figure 6.1 (Updated) Decision tree for estimation of GHG emissions from electronics manufacturing



For semiconductor 450 mm substrate size, facilities should test and develop measured emission factors (Tier 3a). Tier 2a should not be used for 450 mm. Measured factors can be phased in over time; previous generation Tier 2c default factors can be used during the phase in period. Tier 3a measured factors should be submitted to IPCC EFDB to allow development of Tier 2 defaults. See section "Adapting Tier 2 Methods to account for technological changes" for more details.

Tables 6.3 (for gaseous FCs) and 6.4 (for liquid FCs) present the information necessary for completing emissions estimates for each tiered method and lists all the variables that appear in the equations of each method. Depending on the method, variables may either be default values (denoted as 'D' and provided within this document (see section 6.2.2)), or variables may be measured (denoted as 'Me'), modelled (denoted as 'Mo'), or calculated (denoted as 'C' for every variable appearing on the left side of the equal sign in an equation).

TABLE 6.3 (UPDATED)
INFORMATION SOURCES NECESSARY FOR COMPLETING THE TIERED EMISSIONS ESTIMATING METHODS FOR GASEOUS FCS FOR ELECTRONICS MANUFACTURING

Note: The names of the variables have been simplified for the purpose of Table 6.3; please refer to the equations in each tiered methodology for the complete definitions of the variables and their units.
Legend: (Me) = measured; (Mo) = modelled; (D) = default factors from guidance; (C) = calculated.
* These variables are applicable to both sampling period and total year.

	Variables	Tier 1	Tier 2			Tier 3	
			2a	2b	2c	3a	3b
Production	Annual production	P (Me/Mo)					
	Fraction of PV manufacture that uses FC gases	F_{PV} (Me/Mo)					
	δ = 1 when applied to PV industry and zero when applied to either semiconductor or TFT-Display industries, dimensionless	δ (D)					
	Total number of tools running chamber cleaning (IPC and/or ITC) processes		n_i, n_k (Me)	n_i, n_k (Me)n_i (Me)	$n_{i,p}$, $n_{k,p}$ (Me)$n_{i,p}$ (Me)	$n_{i,p}$, $n_{k,p}$ (Me)$n_{i,p}$ (Me)	
	Number of tools running chamber cleaning processes (IPC and/or ITC), and that are equipped with suitable emissions control technologies		na_i, na_k (Me)	na_i, na_k (Me)	$na_{i,p}$, $na_{k,p}$ (Me)	$na_{i,p}$, $na_{k,p}$ (Me)	
	Total number of tools running etch and/or wafer cleaning (EWC) processes		m_i, m_k (Me)	m_i, m_k (Me)	$m_{i,p}$, $m_{k,p}$ (Me)	$m_{i,p}$, $m_{k,p}$ (Me)	
	Number of tools running etch and/or wafer cleaning (EWC) processes, and that are equipped with suitable emissions control technologies		ma_i, ma_k (Me)	ma_i, ma_k (Me)	$ma_{i,p}$, $ma_{k,p}$ (Me)	$ma_{i,p}$, $ma_{k,p}$ (Me)	
Process Gas Entering Tool	Annual consumption of gas		C_i(C)	C_i (C)	$C_{i,p}$ (C)	$C_{i,p}$ (C)	$C_{i,f}$ (Me/Mo)
	Inventory of input gas stored in containers at the beginning of the reporting year		IB_i (Me)	IB_i (Me)	IB_i (Me)	IB_i (Me)	IB_i (Me)
	Inventory of input gas stored in containers at the end of the reporting year		IE_i (Me)	IE_i (Me)	IE_i (Me)	IE_i (Me)	IE_i (Me)
	Acquisitions of input gas during the year		A_i (Me)	A_i (Me)	A_i (Me)	A_i (Me)	A_i (Me)

TABLE 6.3 (UPDATED) (CONTINUED)
INFORMATION SOURCES NECESSARY FOR COMPLETING THE TIERED EMISSIONS ESTIMATING METHODS FOR GASEOUS FCS FOR ELECTRONICS MANUFACTURING

Note: The names of the variables have been simplified for the purpose of Table 6.3; please refer to the equations in each tiered methodology for the complete definitions of the variables and their units.
Legend: (Me) = measured; (Mo) = modelled; (D) = default factors from guidance; (C) = calculated.
* These variables are applicable to both sampling period and total year.

	Variables	**Tier 1**	**Tier 2**			**Tier 3**	
			2a	**2b**	**2c**	**3a**	**3b**
Process Gas Entering Tool	Transfers of input gas		T_i (C)	T_i (C)	T_i (C)	T_i (C)	T_i (C)
	Heel factor		$h_{i,c}$ (D/Me)	$h_{i,c}$ (D/Me)	$h_{i,c}$ (D/Me)	$h_{i,c}$ (D/Me)	$h_{i,c}$ (D/Me)
	Number of containers		$N_{i,c}$ (Me)	$N_{i,c}$ (Me)	$N_{i,c}$ (Me)	$N_{i,c}$ (Me)	$N_{i,c}$ (Me)
	Full capacity of containers		$F_{i,c}$ (Me)	$F_{i,c}$ (Me)	$F_{i,c}$ (Me)	$F_{i,c}$ (Me)	$F_{i,c}$ (Me)
	Total number of container types		M (Me)	M (Me)	M (Me)	M (Me)	M (Me)
	Apportioning factor		$\Phi_{i,p}$ (Me/Mo)	$\Phi_{i,p}$ (Me/Mo)	$\Phi_{i,p}$ (Me/Mo)	$\Phi_{i,p}$ (Me/Mo)	
Process	Emission Factor	EF_i (D)					
	Use rate of gas		U_i (D)	U_i (D)	$U_{i,p}$ (D)	$U_{i,p}$ (Me)	
	By-product emission factor		$B_{k,i}$ (D)	$B_{k,i}$ (D)	$B_{k,i,p}$ (D)	$B_{k,i,p}$ (Me)	
Downstream Emissions Control	Destruction Removal Efficiency (DRE)		d_i, d_k (D)	d_i, d_k (D)	$d_{i,p}$, $d_{k,p}$ (D)	$d_{i,p}$, $d_{k,p}$ (D/Me)	d_i , d_k (D/Me)
	Overall reduction of emissions		D_i, D_k (C)	D_i, D_k (C)	$D_{i,p}$, $D_{k,p}$ (C)	$D_{i,p}$, $D_{k,p}$ (C)	
	Mass fraction of NF_3 or F_2 in process exhaust gas that is converted into CF_4 by direct reaction with hydrocarbon fuel and F_2 gas in a combustion emissions control system.		$AB_{i,CF4}$ (D)	$AB_{i,CF4}$ (D)	$AB_{i,CF4}$ (D)	$AB_{i,CF4}$ (D)	
	Ratio of uncontrolled emissions per-tool from tools running chamber cleaning processes to uncontrolled emissions per-tool from process tools running EWC processes		γ_i, γ_k (D)	γ_i, γ_k (D)			
	Ratio of emissions control systems certified not to form CF_4 within emissions control systems to the total number of emissions control systems in the facility		η (Me)	η (Me)	η_p (Me)	η_p (Me)	
	Estimate of the fraction of gas emitted from process tools equipped with suitable emissions control technologies		a_i, a_k (C)	a_i, a_k (C)	$a_{i,p}$, $a_{k,p}$ (C)	$a_{i,p}$, $a_{k,p}$ (C)	$a_{i,f}$, $a_{k,f}$ (C)

Table 6.3 (Updated) (Continued)
Information sources necessary for completing the tiered emissions estimating methods for gaseous FCs for Electronics Manufacturing

Note: The names of the variables have been simplified for the purpose of Table 6.3; please refer to the equations in each tiered methodology for the complete definitions of the variables and their units.
Legend: (Me) = measured; (Mo) = modelled; (D) = default factors from guidance; (C) = calculated.
* These variables are applicable to both sampling period and total year.

	Variables	**Tier 1**	**Tier 2**			**Tier 3**	
			2a	**2b**	**2c**	**3a**	**3b**
Downstream Emissions Control	Uptime factor of emissions control systems		UT (C)	UT (C)	UT_p (C)	UT_p (C)	UT_f (C)*
	Total time that emissions control system connected to process tool(s) in the plant is not in operational mode when at least one of the manufacturing tools connected to emissions control system is in operation		Td_n (Me)	Td_n (Me)	$Td_{n,p}$ (Me)	$Td_{n,p}$ (Me)	$Td_{n,f}$ (Me)*
	Total time during which emissions control system has at least one associated manufacturing tool in operation		TT_n (Me)	TT_n (Me)	$TT_{n,p}$ (Me)	$TT_{n,p}$ (Me)	$TT_{n,f}$ (Me)*
Stack Test Specific	Flow rate of stack system during the sampling period						Q_s (Me)
	Molecular weight of gas						MW_i, MW_k (D)
	Standard molar volume of gas						SV (D)
	Average concentration of input gas in stack system during sampling						$X_{i,s,m}$, $X_{k,s,m}$ (Me)
	Length of time interval m in the FTIR sampling period						Δt_m (Me)
	Total number of time intervals m in sampling period						N (C)
	Consumption of input gas during the sampling period						$Activity_{i,f}$ (Me)
	Facility-specific emission factor						$EF_{i,f}$, $EF_{k,f}$ (C)
Emissions	Emissions of FC gases or N_2O	$\{E_i\}_n$ (C)					
	Emissions of unreacted input gas		E_i (C)	E_i (C)	E_i (C)	E_i (C)	$EA_{i,f}$, $ES_{i,s}$ (C)
	Emissions of by-products		BPE_k (C)	BPE_k (C)	BPE_k (C)	BPE_k (C)	$EA_{k,f}$, $ES_{k,s}$ (C)
	Emissions of CF_4 from hydrocarbon-fuel-based combustion emissions control systems		$EAB_{i,CF4}$ (C)	$EAB_{i,CF4}$ (C)	$EAB_{i,CF4}$ (C)	$EAB_{i,CF4}$ (C)	

TABLE 6.4 (UPDATED)
INFORMATION SOURCES NECESSARY FOR COMPLETING THE TIERED EMISSIONS ESTIMATING METHODS FOR LIQUID FCS FOR ELECTRONICS MANUFACTURING

Legend: (Me) = measured; (Mo) = modelled; (D) = default factors from guidance; (C) = calculated.
* These variables are applicable to both sampling period and total year.

	Tier 1	Tier 2
Annual production either in m^2 of substrate used during the production of electronic devices (for heat transfer fluid applications) or in thousands of packaged devices (for testing, packaging and soldering)	P (Me)	
Emission factor for fluorinated liquid aggregate emissions either per m^2 of substrate consumed during the period (kg/m^2, for heat transfer fluid applications), or per thousand packaged devices (kg/kpcs, for testing, packaging and soldering)	EF_i (D)	
Density of fluorinated liquid		ρ_i (Me)
Inventory of fluorinated liquid in containers other than equipment at the beginning of the reporting year		I_{it-1} (Me)
Acquisitions of fluorinated liquids during the reporting year, including amounts purchased from chemical suppliers, amounts purchased from equipment suppliers with or inside of equipment, and amounts returned to the facility after off-site recycling		$P_{i,t}$ (Me)
Total nameplate capacity of equipment that uses fluorinated liquids and that is newly installed in the facility during the reporting year		$N_{i,t}$ (Me)
Total nameplate capacity of equipment that uses fluorinated liquids and that is removed from service in the facility during the reporting year		$R_{i,t}$ (Me)
Inventory of fluorinated liquids in containers other than equipment at the end of the reporting year		$I_{i,t}$ (Me)
Disbursements of fluorinated liquids, including amounts returned to chemical suppliers, sold with or inside of equipment, and sent off-site for verifiable recycling or destruction		$D_{i,t}$ (Me)
Emissions of fluorinated liquid	FC_i (C)	FC_i (C)

TIER 1 METHOD – DEFAULT EMISSION FACTORS BASED ON PRODUCTION

The Tier 1 method is the least accurate estimation method and should be used only in cases where facility-specific data are not available. The Tier 1 method is based on production figures (surface area of substrate used during the production of electronic devices, e.g. silicon, glass). Unlike the Tier 2 or Tier 3 methods, the Tier 1 method is designed to give an aggregated estimate of greenhouse gas and N_2O emissions with an estimated but uncertain break-out among specific gases. Estimates are made simultaneously for all the gases listed in Table 6.6, and the Tier 1 method can only be used if these gases are reported as a complete set. For each class (sub-sector) of electronic products being manufactured (semiconductors, display, PV, MEMS), the calculation of emissions relies on a different set of default, gas-specific emission factors. Each default emission factor expresses the average emissions of the relevant gas per unit area of the relevant substrate used during manufacture (including test substrates).

For any class of electronic products (input material), the default emission factors are multiplied by the annual production (P, in units of square meters (m^2)). The result is a set of annual emissions estimates expressed in kg of the gases emitted during the manufacture of that class of electronic products. Because the use of greenhouse gases varies widely during PV manufacture, a third factor to account for the proportion of PV manufacture that employs process greenhouse gases is needed to estimate emissions from PV cells manufacturing. The Tier 1 formula is shown in Equation 6.1.

EQUATION 6.1 (UPDATED)
TIER 1 METHOD FOR ESTIMATION OF THE SET OF GHG EMISSIONS

$$\{E_i\}_n = \{EF_i \bullet P \bullet [F_{PV} \bullet \delta + (1-\delta)]\}_n \quad (\mathrm{i} = 1, \ldots, \mathrm{n})$$

Where:

$\{E_i\}_n$ = emissions of fluorinated compound gas i (FC_i) or N_2O, kg

Note: $\{\ \}_n$ denotes the set for each class of products (semiconductors, display, MEMS, or PV) and *n* denotes the number of gases included in each set ({#} for semiconductors, {#} for display, {#} for MEMS, and {#} for PV, see Table 6.6). The estimates are only valid if made and reported for all members of the set using this Tier 1 methodology

EF_i = emission factor for gas i expressed as annual mass of emissions per square meters of substrate surface area for the product class, mass of gas i/m^2. See default factors of Table 6.6

P = annual production, m^2 of substrate used as measured by the surface area of substrate used during the production of electronic devices, including test substrates. If annual production is not available from an electronics producer, P may be calculated as the product of the annual manufacturing capacity and annual plant production capacity utilisation (fraction) of that producer

F_{PV} = fraction of PV manufacture that uses FC gases, fraction

δ = 1 when Equation 6.1 is applied to PV industry and zero when Equation 6.1 is applied to either semiconductor or TFT-Display industries, dimensionless

i = input gas

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

In using Tier 1, inventory compilers should not modify, in any way, the set of the gases assumed in Table 6.6. For any given manufacturing facility, inventory compilers should not combine emissions estimated using Tier 1 method with emissions estimated using the Tier 2 or 3 methods. Neither may inventory compilers use, for example, the Tier 1 factor for CF_4 to estimate the emissions of CF_4 from semiconductors and combine it with the results of other FC gases from a Tier 2 or Tier 3 method. (See also Section 6.2.2.1.)

GAS CONSUMPTION AND APPORTIONING FOR TIERS 2 AND 3

In using the Tier 2 and Tier 3a methods, input gas consumption (C_i) should be determined and apportioned to specific process types ($C_{i,\,p}$). Where the Tier 2c or 3a methods are used to estimate emissions from a semiconductor facility that manufactures on multiple wafer sizes, gas consumption should be apportioned to specific wafer sizes as well. In this situation, the equations below can be used twice, substituting "wafer size" for "process" as a first step and then using the equation again for "process". Total annual input gas i consumption (C_i) on a facility basis for each fluorinated compound and N_2O is calculated using Equation 6.2 below.

EQUATION 6.2 (NEW)
CONSUMPTION OF INPUT GAS I

$$C_i = \left(IB_i - IE_i + A_i - T_i\right)$$

Where:

C_i = annual consumption of input gas i (site specific), kg per year

IB_i = inventory of input gas i stored in containers at the beginning of the reporting year, including heels, kg. For containers in service at the beginning of a reporting year, account for the quantity in these containers as if they were full.

IE_i = inventory of input gas i stored in containers at the end of the reporting year, including heels, kg. For containers in service at the end of a reporting year, account for the quantity in these containers as if they were full

A_i = acquisitions of input gas i during the year through purchases or other transactions, including heels in containers returned to the electronics manufacturing facility, kg

T_i = transfers of input gas i through sales or other transactions during the year, including heels in containers returned by the electronics manufacturing facility to the chemical supplier, as calculated using Equation 6.3, kg

i = input gas.

Transfers (T_i) are calculated using Equation 6.3.

EQUATION 6.3 (NEW)
TRANSFERS OF INPUT GAS I

$$T_i = \sum_{c=1}^{M} h_{i,c} \bullet N_{i,c} \bullet F_{i,c}$$

Where:

T_i = transfers of input gas i through sales or other transactions during the reporting year for the reporting facility, including heels in containers returned by the electronics manufacturing fab to the gas distributor, kg

$h_{i,c}$ = gas-specific heel factor for input gas i and container size and type c, fraction. A default $h_{i,c}$=0.1 may be used instead of developing gas-specific, container-specific factors

$N_{i,c}$ = number of containers of size and type c used at the reporting facility and returned to the gas distributor containing the standard heel of input gas i

$F_{i,c}$ = full capacity of containers of size and type c containing input gas i, kg

i = input gas

c = size and type of gas container

M = total number of different sized container types for the reporting facility. If only one size and container type is used for an input gas i, M = 1

A site-specific heel factor for each type of gas and container used in a facility ($h_{i,c}$) can be determined by monitoring the pressure and converting the pressure to mass using the ideal gas law or based on the weight of the gas provided to the facility in gas supplier documents. If the reporting facility uses less than 50 kg of an FC gas or N_2O in one reporting year, inventory compilers may assume that any $h_{i,c}$ for that FC gas or N_2O is equal to zero.

For the Tier 2 and Tier 3a methods, varying degrees of gas use apportioning are required. For the semiconductor sub-sector, the Tier 2a and 2b methods require apportioning of NF_3 and C_3F_8 consumption between the remote plasma clean (RPC) process type and other NF_3- or C_3F_8-using process types, while N_2O is apportioned between the N_2O TFD process type and "Other" N_2O-using process types. The Tier 2c (for the semiconductor, MEMS, and display sub-sectors) and the Tier 3a (for all sub-sectors) methods require apportioning for each input gas i and each process type p. Apportioning is calculated using Equation 6.4.

EQUATION 6.4 (NEW)
APPORTIONING OF C TO PROCESS TYPES/SUB-TYPES

$$C_{i,p} = C_i \bullet \Phi_{i,p}$$

Where:

$C_{i,p}$ = annual amount of input gas i consumed by the reporting facility for process type p, kg

$\Phi_{i,p}$ = process type p-specific apportioning factor for input gas i, fraction

C_i = annual consumption of input gas i for the reporting facility, as calculated using Equation 6.2, kg

i = input gas

To minimize apportioning uncertainty and increase accuracy, it is *good practice* to implement a gas consumption monitoring system using direct measurement to apportion gas use at the process type-, stack system- or facility-level as appropriate. This can be achieved by various methods including monitoring and integrating the signal of Mass Flow Controllers (MFCs) and using weigh scales; however, it is noted that measurement to specific tools or processes may not be feasible. If gas consumption measurement at the process level is not deemed feasible for a particular facility, apportioning factors ($\Phi_{i,p}$) can be calculated using a site-specific engineering model. This model should be based on a quantifiable metric, such as substrate passes or substrate starts. To verify the apportioning model, it is *good practice* to demonstrate its precision and accuracy as follows:

(1) Demonstrate that the FC gases and N_2O apportioning factors are developed using calculations that are repeatable, which means that the variables used in the formulas for the facility's engineering model for gas apportioning factors should be based on observable and measurable quantities that govern gas consumption rather than engineering judgment about those quantities or gas consumption. Note that research and development (R&D) and tool commissioning activities may be excluded from the apportioning calculations, but that gas purchases in support of these activities should be included in the emissions calculation. In the event of the introduction of new manufacturing technologies or new gases, this demonstration should be repeated.

(2) Demonstrate the accuracy of the site-specific apportioning model by comparing the actual amount of input gas i consumed and the modelled amount of input gas i consumed in the facility, by:

(i) Analysing actual and modelled gas consumption for a sustained period (at least 30 days) when the fab is at a representative operating level (at least 70 percent of the average production rate for the year in terms of monthly substrate starts). In the event of the introduction of new technologies or substrate size this analysis should be repeated.

(ii) Comparing the actual gas consumed to the modelled gas consumed for the highest use fluorinated compound (or compounds) used in multiple process types at the facility (e.g., NF_3 use in remote plasma clean and other processes).

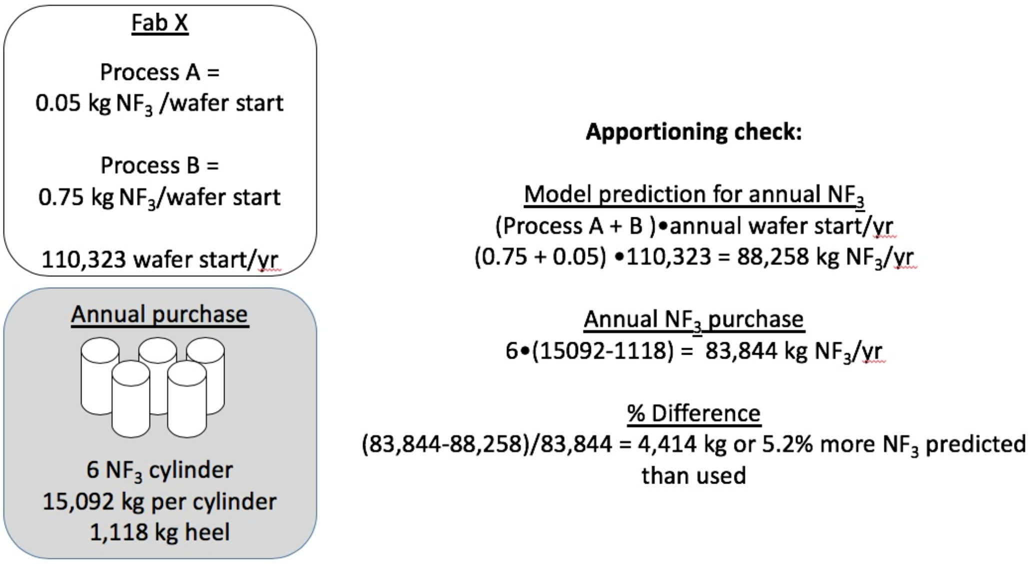
(iii) Demonstrating that the comparison performed for the largest quantity of gas(es), on a mass basis, consumed in the facility, does not result in a difference between the actual and modelled gas consumption that exceeds 20 percent relative to actual gas consumption.

(iv) If 20 percent is not achieved, the model should be revised until the difference between actual and the modelled gas consumption does not exceed 20 percent.

Note that inventory compilers may use a combination of apportioning factors developed using a facility-specific engineering model and apportioning factors developed through the use of direct measurement.

Box 6.1 provides an example of a site-specific apportioning model verification.

BOX 6.1 (NEW)
SITE-SPECIFIC APPORTIONING MODEL VERIFICATION EXAMPLE



Fab X

Process A =
0.05 kg NF_3 /wafer start

Process B =
0.75 kg NF_3/wafer start

110,323 wafer start/yr

Annual purchase

6 NF_3 cylinder
15,092 kg per cylinder
1,118 kg heel

Apportioning check:

Model prediction for annual NF_3
(Process A + B)•annual wafer start/yr
(0.75 + 0.05) •110,323 = 88,258 kg NF_3/yr

Annual NF_3 purchase
6•(15092-1118) = 83,844 kg NF_3/yr

% Difference
(83,844-88,258)/83,844 = 4,414 kg or 5.2% more NF_3 predicted than used

TIER 2 METHODS – DEFAULT EMISSION FACTORS BASED ON GAS CONSUMPTION

Tier 2a Method

The Tier 2a method is applicable to semiconductor manufacturing and to MEMS manufacturing that is carried out using tools and processes similar to those used to manufacture semiconductors (for further details see discussion in the Choice of method section, in particular footnote 3). As discussed above, the Tier 2a method does not distinguish between wafer sizes or among process types for most FCs; however, the Tier 2a method does provide different default emission factors for C_3F_8 RPC vs. other C_3F_8-using processes, for NF_3 RPC vs. other NF_3-using processes, and for N_2O TFD processes vs. 'other' N_2O-using processes. Thus, when using the Tier 2a method, the consumption of C_3F_8 and NF_3 should be apportioned between RPC and other processes, and consumption of N_2O should be apportioned between TFD and "Other" N_2O-using processes, as applicable to each reporting site.

The Tier 2a method uses the default emission factors provided in Table 6.7, which represent average utilisation efficiencies of the gases used in manufacturing processes (U_i) and the formation of by-products during the use of each input gas i ($B_{k,i}$). The other default factors used for the Tier 2a method include the destruction removal efficiency of gases i and by-products k (d_i, d_k - see Table 6.17) and the ratio of per-tool uncontrolled emissions of gases i (and by-products k) from TFD process tools to per-tool uncontrolled emissions of gases i (and by-products k) from EWC process tools (γ_i, γ_k - see Table 6.8).

The Tier 2a method also uses site-specific data on gas consumption and emissions control. Inventory compilers using the Tier 2a method should directly communicate with industry to gather consumption and emissions control-related data and to ensure that reductions are not attributed to emissions control devices unless the devices are installed and used in accordance with the guidance provided in section 6.2.2.1. Inventory compilers should note that the consumption of gas i (Ci) takes into account the heel factor (hi,l), which represents the fraction of gas i remaining in the shipping container after use, and which can be based on industry-wide default or site-specific measured values (see Section on Gas Consumption and Apportioning).

Total Tier 2a emissions are calculated using Equations 6.5, 6.6, and 6.7 below, and are equal to the sum of emissions from all unreacted gases i used in the production process (E_i), plus emissions of all by-products k (BPE_k) resulting from the conversion of all input gases i used during production, plus emissions of CF_4 from hydrocarbon-fuel-based combustion emissions control systems ($EAB_{i,CF4}$). However, note that $EAB_{i,CF4}$ may be set equal to zero if the emissions control equipment manufacturer can certify that reactions between hydrocarbon fuel and F_2 to form CF_4 are not occurring within their emissions control systems (i.e. certify that $AB_{i,CF4} = 0$).

EQUATION 6.5 (UPDATED)
EMISSIONS OF INPUT GAS I

$$E_i = C_i \bullet \left(1 - U_i\right) \bullet \left(1 - D_i\right)$$

Where:

E_i = emissions of unreacted input gas i, kg

C_i = consumption of input gas i, kg

U_i = use rate of gas i (fraction destroyed or transformed in process), fraction

D_i = overall reduction of mass of gas i emissions, site-specific fraction, calculated per Equation 6.8

i = input gas

EQUATION 6.6 (UPDATED)
BY-PRODUCT EMISSIONS

$$BPE_k = \sum_i [C_i \bullet B_{k,i} \bullet (1 - D_k)]$$

Where:

BPE_k = emissions of by-product k generated from the conversion of all input gases i, kg

C_i = consumption of input gas i, kg

$B_{k,i}$ = emission factor for by-product k generated from input gas i, kg of by-product gas k created/kg of gas i consumed

D_k = overall reduction of mass of gas k by-product emissions, site-specific fraction, calculated per Equation 6.9

i = input gas

k = by-product gas

BOX 6.2 (NEW)
FLUORINATED GREENHOUSE GAS BY-PRODUCTS

As discussed briefly in the introduction, the formation of fluorinated GHG by-products resulting from the decomposition of input gases or from the reaction with the materials being etched or cleaned should be taken into account. To this effect, by-product emission factors ($B_{CF4,i}$, $B_{C2F6,i}$, $B_{C3F8,i}$, $B_{C4F6,i}$, $B_{C4F8,i}$, $B_{C5F8,i}$, $B_{CH3F.i}$ $B_{CH2F2,i}$, and $B_{CHF3,i}$, emission factors indicating the mass ratio of by-product produced from the use of input gas i) are included as part of the default emission factors tables for the Tier 2 methods. In some cases, perfluorinated carbon by-product emission factors are provided, even when the etching or cleaning gas i itself contains fluorine but does not contain carbon (e.g. NF_3, SF_6, F_2). This is because the fluorine atoms and other excited F species generated from the decomposition of NF_3, SF_6 or F_2 can react with the carbon contained in the film to form CF_4 and other carbon-containing greenhouse gas by-products. Such reactions are particularly significant during the etching or cleaning of 'low k' (low dielectric constant) materials that often present high carbon content, but formation of carbon-containing by-products also occur when small amounts of carbon are present in the film, for example in the case of thin films deposited with organic precursors such as tetraethylorthosilicate (TEOS). However, when using NF_3, SF_6, F_2 or other etching or cleaning precursors that do not contain carbon, and when the film being etched or cleaned does not contain carbon, then no CF_4 or other carbon-containing greenhouse gases are expected to be formed during the process.

As noted in Box 6.2 the formation of FC gas by-products such as CF_4, C_2F_6, CH_3F, CH_2F_2, and CHF_3 can occur when etching or cleaning carbon-containing films, even when input gases do not contain carbon (e.g. NF_3, SF_6, F_2). However, when using NF_3, SF_6, F_2 or other etching or cleaning precursors that do not contain carbon, and when the film being etched or cleaned does not contain carbon, then no CF_4 or other carbon-containing greenhouse gases are formed during the process. Thus, in such cases (and in such cases only), the $B_{k,i}$ factors may be set equal to zero in Equation 6.6. It should be noted, however, that sometimes both carbon-containing and non-carbon-containing films are included in the film stacks forming final electronic devices. In such cases, there are two options: 1) if it is practical to track the gas consumption used to clean or etch films containing carbon vs. not containing carbon, the non-zero and zero $B_{k.i}$ factors may be applied accordingly, or 2) if it is not practical or desired to track gas consumption to this level of detail, the non-zero BPE factors should be applied to all consumption of a gas if any film containing carbon is run with that gas during the year.

Emissions and emission reductions from emission control devices

When NF_3 is used in RPC processes or F_2 is used as an input gas and when hydrocarbon-fuel-based combustion emissions control technology is used, direct reaction with hydrocarbon fuel and F_2 (including F_2 resulting from the decomposition of NF_3 in RPC processes) to form CF_4 can occur. Unless the emissions control system manufacturer (referred to below as the "original equipment manufacturer" or "OEM") or electronics manufacturer can certify that the rate of conversion from F_2 to CF_4 or from NF_3 to CF_4 is <0.1 percent on a mass basis, Equation 6.7 should be used to estimate the amount of CF_4 produced within and emitted from the emissions control equipment.

EQUATION 6.7 (NEW)
BY-PRODUCT EMISSIONS FROM HYDROCARBON FUELLED COMBUSTION EMISSIONS CONTROL SYSTEMS

$$EAB_{i,CF_4} = C_i \bullet (1 - U_i) \bullet (1 - \eta) \bullet AB_{i,CF_4}$$

Where:

i = input gas (i = only NF_3 used in RPC processes or F_2 for the purpose of Equation 6.7)

EAB_{i,CF_4} = emissions of CF_4 from hydrocarbon-fuel-based combustion emissions control systems when direct reaction with hydrocarbon fuel and fluorinated species is not certified not to occur by the emissions control OEM or electronics manufacturer, kg

C_i = consumption of gas i (i = only NF_3 used in RPC processes or F_2 for the purpose of Equation 6.7), kg

U_i = use rate of gas i, fraction destroyed or transformed in process

η = ratio of emissions control systems certified not to form CF_4 within emissions control systems to the total number of emissions control systems in the facility, site-specific fraction

AB_{i,CF_4} (i = only NF_3 used in RPC processes or F_2 for the purpose of Equation 6.7) = mass fraction of NF_3 used in RPC processes or F_2 in process exhaust gas that is converted into CF_4 by direct reaction with hydrocarbon fuel and F_2 gas in a combustion emissions control system. AB_{i,CF_4} is set to zero if the emissions control OEM or electronics manufacturer can certify that the rate of conversion from F_2 to CF_4 or from NF_3 to CF_4 is <0.1 percent; otherwise, a default value of $AB_{NF_3,CF_4} = 0.093$ or $AB_{F_2,CF_4} = 0.116$ should be used.

Inventory compilers should calculate the overall reductions in emissions of process gas i and by-product k ($D_{i,p}$, $D_{k,p}$) based on site-specific information using Equations 6.8 and 6.9, factoring in the mass fraction of gas i and by-product k emitted from process tools equipped with suitable emissions control technologies (a_i, a_k), the destruction removal efficiency of gas i and by-product k (di, d_k), and the average uptime of emissions control systems (UT).

EQUATION 6.8 (NEW)
EMISSIONS REDUCTION IMPACT OF EMISSIONS CONTROL TECHNOLOGY FOR GAS I

$$D_i = a_i \bullet d_i \bullet UT$$

Where:

D_i = overall reduction of mass of gas i emissions, site-specific fraction

a_i = estimate of the fraction of gas i emitted from process tools equipped with suitable emissions control technologies, site-specific fraction, as determined in Equation 6.10 or Equation 6.18, as applicable

d_i = Destruction Removal Efficiency (DRE) for gas i, fraction

UT = average uptime factor of all emissions control systems, site-specific fraction, calculated per Equation 6.12

i = input gas

EQUATION 6.9 (NEW)
EMISSIONS REDUCTION IMPACT OF EMISSIONS CONTROL TECHNOLOGY FOR BY-PRODUCT K

$$D_k = a_k \bullet d_k \bullet UT$$

Where:

D_k = overall reduction of mass of by-product k emissions, site-specific fraction

a_k = estimate of the fraction of by-product emitted from process tools equipped with suitable emissions control technologies, site-specific fraction, as determined in Equation 6.11 or Equation 6.19, as applicable

d_k = Destruction Removal Efficiency (DRE) for by-product k, fraction

UT = average uptime factor of all emissions control systems, site-specific fraction, calculated per Equation 6.12

k = by-product gas

Calculation of a_i and a_k using the default weighting factors γ_i and γ_k

When using the Tier 2a method, inventory compilers should calculate the fractions of gas i and by-products k (based on mass) emitted from process tools equipped with suitable emissions control technologies (a_i and a_k). "Suitable" means that an emissions control technology is capable of abating a particular gas to a minimum destruction removal efficiency in a site-specific worst-case scenario (please see Section 6.2.2.1 on Emissions Control Technology Factors for more details).

For NF_3 and C_3F_8 used in RPC processes, and for N_2O used in either TFD or "other" processes, inventory compilers should use Equations 6.18 and 6.19 to estimate the fractions of the input gas and associated by-product abated for each of those process types ($a_{i,p}$ and $a_{k,p}$). For other input-gas and process-type combinations, inventory compilers should use Equations 6.10 and 6.11 to estimate the fractions of input gas and by-product abated across multiple process types (a_i and a_k) based on the default weighting factors (γ_i and γ_k) provided in Table 6.8.

As discussed in Box 6.3, the gamma factors reflect the ratio of uncontrolled emissions per tool of gas i or by-product k from tools running chamber cleaning processes (in-situ plasma (IPC) and/or in-situ thermal (ITC)) to the uncontrolled emissions per tool of gas i or by-product k from tools running etch and/or wafer cleaning (EWC) processes. Taking gamma values into account is necessary when (1) an input gas is consumed (or a by-product k is produced) both by chamber cleaning processes and by EWC processes, (2) the use of the input gas is not apportioned between chamber cleaning processes and EWC processes, and (3) the fractions of tools equipped with emissions control technologies are different for chamber cleaning processes and EWC processes. To calculate a_i and a_k, inventory compilers should use Equations 6.10 and 6.11 and the default gamma factors, as well as the total number of tools in the reporting facility using gas i or producing by-product k (n_i, m_i, n_k, m_k), and the number of those tools equipped with suitable emissions control technology for gas i or by-product k ($n_{a,i}$, $m_{a,i}$, $n_{a,k}$, $m_{a,k}$)[6].

For each gas where a value for γ_i or γ_k exists, Table 6.8 provides gamma values relating per-tool emissions from IPC processes (and, in some cases, per-tool emissions from ITC processes as well) to per-tool emissions from EWC processes. The gamma value column selected by a facility depends on the gas(es) emitted by the facility and the chamber cleaning process(es) used by the facility. The gamma value row depends on the Tier 2 method used (a or b) by the facility, whether the gas is emitted as an input gas or by-product, and (for Tier 2b), the wafer size. For example, a facility emitting CF_4 from IPC processes, ITC processes, or both would use a gamma value from the second column from the left in Table 6.8. If the facility were using the Tier 2a method to estimate emissions of CF_4 as an input gas, it would use the γ_i value in the row immediately below the "Tier 2a" title row in the table. The corresponding equipment count n_i would be the total number of pieces of equipment that emit CF_4 as an input gas and that run either IPC or ITC processes, and the corresponding equipment count na_i would be the total number of pieces of equipment that emit CF_4 as an input gas, that run either IPC or ITC processes, and that are abated. (If the facility emits CF_4 as an input gas from both IPC and ITC processes, n_i and na_i are the sum of the applicable equipment counts across the two process types.)

Where a facility requires a gamma value for a gas-process type combination that is not covered by the table (e.g., c-C_4F_8 ITC), the facility should use a default gamma value of 10.

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[6] As tools running etch and/or wafer cleaning process often use multiple input gases that may each produce CF_4 or C_2F_6 as a by-product, inventory compilers should be careful not to double count when totalling the number of etch tools that produce by-product k (m_k) and the total number etch tools that produce by-product-k that are abated (ma_k). Values for ma_k and m_k should not exceed the total number of tools that run etch and/or wafer cleaning processes in the fab.

BOX 6.3 (NEW)
THE IMPORTANCE AND LIMITATIONS OF THE DEFAULT GAMMA VALUES FOR CALCULATING A_I AND A_K

To estimate the fraction of an FC abated when that FC is emitted from both chamber cleaning processes and EWC processes, the Tier 2a and 2b methods apply default weighting factors (γ_i and γ_k) to the numbers of abated and unabated tools running chamber cleaning processes (see Equations 6.10 and 6.11). These default weighting factors have been introduced in the Refinement because, for most FCs, the Tier 2a and 2b methods do not otherwise track per-tool emissions by process type (i.e., through apportioning), and per-tool emissions can vary significantly between process types. For example, C_2F_6 input gas flows (and emissions) for chamber cleaning processes can typically be in the order of one or more litres per minute while C_2F_6 input gas flows (and emissions) for etching processes are only typically in the order of one tenth to a few tenth of litres per minute. These differences are reflected in the default gamma values, which range from 2.6 to 26.0. Not accounting for such differences (that is, using unweighted tool counts) could result in large errors in the emissions estimate when the fraction of process tools equipped with emissions control technologies is different for different process types. *(Note: Where the Tier 2a and 2b methods do track emissions and emission reductions by process type, that is, for NF_3 and C_3F_8 used in remote plasma clean processes and for N_2O used in either TFD or "other" processes, Equations 6.18 and 6.19 should be used to calculate the fractions of input gas and by-products abated for each of those process types.)*

Default gamma values have been calculated based on the consumption patterns of representative semiconductor manufacturing facilities, accounting for the emissions of unreacted gases i and by-products k as well as for the number of tools emitting gases i or by-products k in such facilities. The default gamma values therefore represent industry averages. However, the gammas found for individual facilities are highly variable depending on gas usage patterns at those facilities. For example, two facilities could have similar numbers of etching tools and use similar total quantities of a particular FC in their etching processes. However, one of the facilities may concentrate their use of that FC in a relatively small subset of their etching tools (e.g., because that FC is the only gas used in that subset of tools), while the other facility may spread their use of that FC across all of their etching tools (e.g., because that FC is used in combination with other FCs in the tools). The per-tool emissions of the FC from etching for the first facility would be much higher than the per-tool emissions of the FC from etching at the second. If the per-tool emissions from TFD tools were the same at both facilities, the first facility's gamma factor (ratio of per-tool emissions from TFD tools to per-tool emissions from etch tools) would be much smaller than the second facility's gamma factor. As a result of such variability, the gamma values are highly uncertain (see Table 6.22) and can lead to errors in emissions estimates.

Because actual (site-specific) γ_i and γ_k values may significantly differ from the defaults used in the Tier 2a and 2b methods, and because – as a result – the Tier 2a method is highly uncertain, inventory compilers are strongly encouraged to apportion gas consumption by process type and to use the Tier 2c method, a hybrid Tier 2c / Tier 3a method, or ultimately a full Tier 3a method. If apportioning gas usage proves problematic for a particular facility, the Tier 3b method could be an alternate approach providing higher accuracy without the need to develop a complex apportioning model for the facility.

EQUATION 6.10 (NEW)
ESTIMATE OF THE MASS FRACTION OF GAS I EMITTED FROM PROCESS TOOLS EQUIPPED WITH EMISSION CONTROL TECHNOLOGIES

$$a_i = \frac{(\gamma_i \bullet na_i + ma_i)}{(\gamma_i \bullet n_i + m_i)}$$

Where:

a_i = estimate of the fraction of gas i emitted from process tools equipped with suitable emissions control technologies, site-specific fraction

na_i = number of tools using gas i, running chamber cleaning processes (IPC and/or ITC), and that are equipped with suitable emissions control technologies for gas i, site-specific

ma_i = number of tools using gas i, running etch and/or wafer cleaning processes, and that are equipped with suitable emissions control technologies for gas i, site-specific

n_i = total number of tools using gas i and running chamber cleaning processes (IPC and/or ITC), site-specific

m_i = total number of tools using gas i and running etch and/or wafer cleaning processes, site-specific

γ_i = default factor reflecting the ratio of uncontrolled emissions per tool of input gas i from tools running chamber cleaning processes (IPC and/or ITC) to uncontrolled emissions per tool of input gas i from process tools running etch and/or wafer cleaning processes, fraction

i = input gas

EQUATION 6.11 (NEW)
ESTIMATE OF THE MASS FRACTION OF BY-PRODUCT K EMITTED FROM PROCESS TOOLS EQUIPPED WITH EMISSION CONTROL TECHNOLOGIES

$$a_k = \frac{(\gamma_k \bullet na_k + ma_k)}{(\gamma_k \bullet n_k + m_k)}$$

Where:

a_k = estimate of the fraction of by-product k emitted from process tools equipped with suitable emissions control technologies, site-specific fraction

na_k = number of tools emitting by-product k, running chamber cleaning processes (IPC and/or ITC), and that are equipped with suitable emissions control technology for by-product k, site-specific

ma_k = number of tools emitting by-product k, running etch and/or wafer cleaning processes, and that are equipped with suitable emissions control technology for by-product k, site-specific

n_k = total number of tools producing by-product k and running chamber cleaning processes (IPC and/or ITC), site-specific

m_k = total number of tools producing by-product k and running etch and/or wafer cleaning processes, site-specific

γ_k = default factor reflecting the ratio of uncontrolled emissions per tool of by-product k from process tools running chamber cleaning processes (IPC and/or ITC) to uncontrolled emissions per tool of by-product k from process tools running etch and/or wafer cleaning processes, fraction

k = by-product gas

Finally, inventory compilers should calculate, for each reporting site, the average uptime of all emissions control systems connected to process tools (UT), using Equation 6.12. To this end, inventory compilers should account for the total time (Td_n) that any emissions control system n connected to process tool(s) in the reporting facility is not in operational mode when at least one of the manufacturing tools connected to emissions control system n is in operation, and the total time (TT_n) in which emissions control system n has at least one associated manufacturing tool in operation. For determining the amount of tool operating time, inventory compilers may assume that tools that were installed for the whole of the year were operated for 525,600 minutes per year. For tools that were installed or uninstalled during the year, inventory compilers should prorate the operating time to account for the days in which the tool was not installed and treat any partial day that a tool was installed as a full day (1,440 minutes) of tool operation. For an emissions control system that has more than one connected tool, the tool operating time is 525,600 minutes per year if at least one tool was installed at all times throughout the year. For tools that are idle with no gas flown through the tool for part of the year, inventory compilers may calculate total tool time using the actual time that gas is flowing through the tool. Inventory compilers should also note that UT may be set to one (1) if suitable backup emissions control equipment or interlocking with the process tool is implemented for each emissions control system. Thus, using interlocked process tools or backup emissions control systems reduces uncertainty by eliminating the need to estimate UT for the reporting facility.

EQUATION 6.12 (NEW)
UPTIME OF EMISSIONS CONTROL SYSTEMS

$$UT = 1 - \frac{\sum_n Td_n}{\sum_n TT_n}$$

Where:

UT = Average uptime factor of all emissions control systems connected to process tools (fraction).

Td_n = Total time that emissions control system n connected to process tool(s) in the plant, is not in operational mode when at least one of the manufacturing tools connected to emissions control system n is in operation ,(minutes per year).

TT_n = Total time during which emissions control system n has at least one associated manufacturing tool in operation,(minutes per year).

N = emissions control system.

Tier 2b method

The Tier 2b method is applicable to the semiconductor sub-sector and to MEMS manufacturing that uses tools and processes similar to those used to manufacture semiconductors (for further details see discussion in the Choice of method section, in particular footnote 3). As discussed in section 6.2.1, the Tier 2b method is preferred over the Tier 2a method unless it is not possible to distinguish gas consumption by wafer size (e.g., for semiconductor manufacturing facilities that process multiple wafer sizes and cannot apportion gas consumption between them). The Tier 2b method uses the same set of equations as the Tier 2a method (Equations 6.5 to 6.12), but distinct U_i, $B_{k,i}$, γ_i, and γ_k default factors are provided by the wafer size being manufactured (≤200 mm vs. 300 mm, see Tables 6.8 and 6.9). With this distinction in mind, all other site-specific Tier 2b factors (which are the same as for the Tier 2a method)-are estimated in the same manner as for the Tier 2a method. Thus, inventory compilers using the Tier 2b method should have direct communication with industry to gather consumption and emissions control-related data and verify that emissions control technologies for which reductions are being claimed are installed and used in accordance with the guidance provided in section 6.2.2.1.

Total Tier 2b emissions are calculated using Equations 6.5, 6.6, and 6.7 and are equal to the sum of emissions from all unreacted gases i used in the production process (E_i), plus emissions of all by-products k (BPE_k) resulting from the conversion of all input gases i used during production, plus emissions of CF_4 from hydrocarbon-fuel-based combustion emissions control systems ($EAB_{i,CF4}$). As in the Tier 2a method, $EAB_{i,CF4}$ may be set to zero if the emissions control equipment manufacturer can certify that reactions between hydrocarbon fuel and F_2 to form CF_4 is not occurring within their emissions control system (i.e. certify that $AB_{i,CF4} = 0$).

Tier 2c method

The Tier 2c method is applicable to the semiconductor, display, and PV sub-sectors, and to MEMS manufacturing that is carried out using tools and processes similar to those used to manufacture semiconductors (for further details see discussion in the Choice of method section, in particular footnote 3). The Tier 2c method is based on a set of equations that account for default emission factors that are provided for distinct process types p ($U_{i,p}$ and $B_{k,i,p}$). In the Tier 2c method for the semiconductor sub-sector, there are six process types p defined as 1) etching and wafer cleaning (EWC), 2) remote plasma cleaning (RPC), 3) in-situ plasma cleaning (IPC), 4) in-situ thermal cleaning (ITC), 5) N_2O TFD, and 6) N_2O 'Other'. In the Tier 2c method for the display sub-sector there are only 4 process types p defined as 1) etching, 2) remote plasma cleaning (RPC), 3) in-situ plasma cleaning (IPC), and 4) N_2O TFD. In the case of the Tier 2c method for the PV subsector, process types are defined as 1) etch and 2) TFD chamber cleaning. In addition, the Tier 2c method provides distinct emission factors for different substrate sizes for the semiconductor sub-sector (≤200 mm and 300 mm), but the Tier 2c method does not distinguish emission factors for different substrate size for the display sub-sector (the same Tier 2c default emissions factors are applicable to display manufacturing tools for generations 4, 5, 6, 7, etc.) and the PV sub-sector.

The $U_{i,p}$ and $B_{k,i,p}$ default emission factors for the Tier 2c method are in included in Tables 6.10 to 6.11 for the semiconductor sub-sector (≤200 mm and 300 mm substrate sizes respectively), Table 6.12 for the display sub-sector, and Table 6.13 for the PV sub-sector. The other default emission factors used for the Tier 2c method are the destruction removal efficiencies (DRE) of gases i and by-products k (d_i, d_k - see Table 6.17), which are assumed to be the same across all sub-sectors and across all Tier 2 methods. The Tier 2c method also uses site-specific factors ($C_{i,p}$, $D_{i,p}$, $D_{k,p}$, η_p, $a_{i,p}$, $a_{k,p}$, $n_{i,p,a}$, $n_{i,p}$, $n_{k,p,a}$, $n_{k,p}$, UT_p, $Td_{n,p}$, $TT_{n,p}$), and inventory compilers using the Tier 2c method should directly communicate with industry to gather consumption and emissions control-related data and to ensure that reductions are not attributed to emissions control devices unless the devices are installed and used in accordance with the guidance provided in section 6.2.2.1. Inventory compilers should note that the consumption of gas i ($C_{i,p}$) takes into account the heel factor ($h_{i,l}$), which represents the fraction of gas i remaining in the shipping container after use, and which can be based on industry-wide default or site-specific measured values (see Section on Gas Consumption and Apportioning).

As discussed in section 6.2.1, the use of the Tier 2c method is preferred over the Tier 2a or Tier 2b methods in the semiconductor sub-sector because the Tier 2c default emission factors are expected to be more accurate than the Tier 2b or 2a factors. However, using the Tier 2c method requires apportioning gas consumption for all gases and process types, which introduces additional complexity. Please see the section on Gas Consumption and Apportioning for further detail. Because site-specific factors should be accounted for ($C_{i,p}$, $D_{i,p}$, $D_{k,p}$, η_p, $a_{i,p}$, $a_{k,p}$, UT_p), inventory compilers using the Tier 2c method should have direct communication with industry to gather consumption and emissions control-related data and to verify that emissions control devices from which emission reductions are claimed are installed and used in accordance with the guidance provided in this document. Inventory compilers should note that the consumption of gas i for process p ($C_{i,p}$) takes into account the heel factor ($h_{i,l}$), which represents the fraction of gas i remaining in the shipping container after use, and which can be based on industry-wide default or site-specific measured values (see Section on Gas Consumption and Apportioning).

Tier 2c total emissions are equal to the sum of emissions from all unreacted gases i used in the production process (E_i) plus the emissions of all by-products k (BPE_k) resulting from the conversion of all input gases i used during production, plus emissions of CF_4 from hydrocarbon-fuel-based combustion emissions control systems ($EAB_{i,CF4}$, which may be set to zero if the emissions control equipment manufacturer can certify that reactions between hydrocarbon fuel and F_2 to form CF_4 is not occurring within their emissions control systems). Tier 2c emissions are calculated using process-type-dependent Equations 6.13 to 6.20.

EQUATION 6.13 (UPDATED)
EMISSION OF INPUT GAS I

$$E_i = \sum_p [C_{i,p} \bullet (1 - U_{i,p}) \bullet (1 - D_{i,p})]$$

Where:

E_i = emissions of unreacted input gas, kg

$C_{i,p}$ = consumption of input gas i for process type p, kg

$U_{i,p}$ = use rate of gas i for process p, fraction destroyed or transformed in process p

$D_{i,p}$ = overall reduction of mass of gas i emitted from process type p, site-specific fraction calculated per Equation 6.16

i = input gas

p = process type

EQUATION 6.14 (UPDATED)
PROCESS BY-PRODUCT EMISSIONS FROM INPUT GAS I

$$BPE_k = \sum_i [\sum_p [C_{i,p} \bullet B_{k,i,p} \bullet (1 - D_{k,p})]]$$

Where:

BPE_k = emissions of by-product k generated from the conversion of all input gases i for all process types p, kg

$B_{k,i,p}$ = emission factor for by-product k generated from input gas i for process type p, kg of by-product k created per kg of gas i consumed for process type p

$C_{i,p}$ = consumption of input gas i for process type p, kg

$D_{k,p}$ = overall reduction of mass of gas k by-product emissions for process type p, site-specific fraction calculated per Equation 6.17

i = input gas

k = by-product gas

p = process type

When neither the gases used nor the films etched or cleaned contain carbon, the $B_{k,i,p}$ factors may be equated to zero in Equation 6.14. When both carbon-containing and non-carbon-containing films are included in the film stacks forming final electronic devices, there are two options: 1) if it is practical to track the gas consumption used to clean or etch films containing carbon vs. not containing carbon, the non-zero and zero $B_{k.i,p}$ factors may be applied accordingly, or 2) if it is not practical or desired to track gas consumption to this level of detail, the non-zero BPE factors should be applied to all consumption of a gas if any film containing carbon is run with that gas during the year. (See Box 6.2 and the discussion under Equation 6.6 for more on this issue.)

When NF_3 is used in RPC processes or F_2 is used as an input gas and when hydrocarbon-fuel-based combustion emissions control technology is used, direct reaction with hydrocarbon fuel and F_2 (including F_2 resulting from the decomposition of NF_3 in RPC processes) to form CF_4 can occur. Unless the emissions control equipment original equipment manufacturer (OEM) or electronics manufacturer can certify that the rate of conversion from F_2 to CF_4 or from NF_3 to CF_4 is <0.1 percent on a mass basis, Equation 6.15 should be used to estimate the amount of CF_4 produced within and emitted from the emissions control device.

EQUATION 6.15 (NEW)
BY-PRODUCT EMISSIONS FROM COMBUSTION EMISSIONS CONTROL EQUIPMENT

$$EAB_{i,CF_4} = \sum_p C_{i,p} \bullet (1 - U_{i,p}) \bullet (1 - \eta_p) \bullet AB_{i,CF_4}$$

Where:

i = input gas (i = only NF_3 used in RPC processes or F_2 for the purpose of Equation 6.15)

$EAB_{i,CF4}$ = emissions of CF_4 from hydrocarbon-fuel-based combustion emissions control systems when direct reaction with hydrocarbon fuel and fluorinated species is not certified not to occur by the emissions control equipment OEM or electronics manufacturer, kg

$C_{i,p}$ = consumption of input gas i for process type p (i = only NF_3 used in RPC processes or F_2 for the purpose of Equation 6.15), kg

$U_{i,p}$ = use rate of gas i for process p, fraction destroyed or transformed in process p

η_p = ratio of emissions control systems connected to tools running process type p and certified not to form CF_4 within emissions control systems to the total number of emissions control systems connected to tools running process type p in the facility, site-specific fraction

$AB_{i,CF4}$ (i = only NF_3 used in RPC processes or F_2 for the purpose of Equation 6.15)

= mass fraction of NF_3 used in RPC processes or F_2 in process exhaust gas that is converted into CF_4 by direct reaction with hydrocarbon fuel and F_2 gas in a combustion emissions control system. $AB_{i,CF4}$ is set to zero if the emissions control equipment OEM or electronics manufacturer can certify that the rate of conversion from F_2 to CF_4 or from NF_3 to CF_4 is <0.1 percent; otherwise, a default value of $AB_{NF3,CF4} = 0.093$ or $AB_{F2,CF4} = 0.116$ should be used.

p = process type (RPC using NF_3 or any process type using F_2 for the purpose of Equation 6.15)

Inventory compilers should calculate the overall reductions in emissions of process gas i and by-product k ($D_{i,p}$, $D_{k,p}$) based on site-specific information using Equations 6.16 and 6.17, factoring in the mass fraction of gas i and by-product k emitted from process tools running process type p and equipped with suitable emissions control technologies ($a_{i,p}$, $a_{k,p}$), the destruction removal efficiency of gas i and by-product k (d_i, d_k), and the average uptime of emissions control systems connected to process tools running process type p (UT_p).

EQUATION 6.16 (NEW)
EMISSIONS REDUCTION IMPACT OF EMISSIONS CONTROL EQUIPMENT ON INPUT GAS I

$$D_{i.p} = a_{i,p} \bullet d_i \bullet UT_p$$

Where:

$D_{i,p}$ = overall reduction of mass of gas i emitted from process type p, fraction

$a_{i,p}$ = estimate of the fraction of gas i emitted from process tools running process type p and equipped with suitable emissions control technologies, site-specific fraction calculated using Equation 6.18

d_i = Destruction Removal Efficiency (DRE) for gas i, fraction

UT_p = average uptime factor of all emissions control systems connected to tools running process type p, site-specific fraction calculated per Equation 6.20

i = input gas

k = by-product gas

p = process type

EQUATION 6.17 (NEW)
EMISSIONS REDUCTION IMPACT OF EMISSIONS CONTROL EQUIPMENT ON BY-PRODUCT K

$$D_{k.p} = a_{k,p} \bullet d_k \bullet UT_p$$

Where:

$D_{k,p}$ = overall reduction of mass of gas k by-product emitted from process type p, site-specific fraction

$a_{k,p}$ = estimate of the fraction of by-product k emitted from process tools running process type p and equipped with suitable emissions control technologies, site-specific fraction calculated using Equation 6.19

d_k = Destruction Removal Efficiency (DRE) for by-product k, fraction

UT_p = average uptime of all emissions control systems connected to tools running process type p, site-specific fraction calculated per Equation 6.20

i = input gas

k = by-product gas

p = process type

The use of gamma weighting factors is not required in the Tier 2c method because uncontrolled emissions from different process types are accounted for separately through gas consumption allocation. Instead, to estimate the site-specific $a_{i,p}$ value, inventory compilers may calculate the ratio of the number of tools running process type p (emitting gas i) that are equipped with suitable emissions control technologies ($a_{i,p,a}$) to the total number of tools running process type p and emitting gas i, using Equation 6.18.“Suitable” means that an emissions control technology is capable of abating a particular gas to a minimum destruction removal efficiency in a site-specific worst-case scenario (please see Section 6.2.2.1 on Emissions Control Technology Factors for more details). Note that inventory compilers may obtain more refined estimates of $a_{i,p}$ by counting the number of process chambers running process type p (emitting gas i) that are connected to suitable emissions control technologies, or by using other site-specific approaches that may be more accurate.

EQUATION 6.18 (NEW)
ESTIMATE OF THE FRACTION OF MASS OF GAS I EMITTED FROM PROCESS P FROM TOOLS EQUIPPED WITH EMISSIONS CONTROL EQUIPMENT

$$a_{i,p} = \frac{n_{i,p,a}}{n_{i,p}}$$

Where:

$a_{i,p}$ = estimate of the fraction of gas i emitted from process tools running process type p and equipped with suitable emissions control technologies, site-specific fraction

$n_{i,p,a}$ = number of process tools running process type p (emitting gas i) that are equipped with suitable emissions control technologies, site-specific

$n_{i,p}$ = total number of process tools running process type p and emitting gas i, site-specific

i = input gas

p = process type

To estimate the site-specific $a_{k,p}$ value, inventory compilers may calculate the ratio of the number of tools running process type p (emitting by-product k) that are equipped with suitable emissions control technologies ($ma_{k,p}$) to the total number of tools running process type p and emitting by-products k, using Equation 6.19. Note that by-product k may be formed from multiple gases i (e.g. CF_4 is produced as a by-product of all other FCs) and that, as shown in Equation 6.19, inventory compilers should count all the tools that are susceptible of emitting by-product k ($m_{k,p}$) by summing up the number of tools emitting by-product k over all gases i, then account for the number of such tools that are equipped with suitable emissions control technologies ($ma_{k,p}$). Note also that inventory compilers may obtain more refined estimates of $a_{k,p}$ by counting the number of process chambers running process type p (emitting by-product k) that are connected to suitable emissions control technologies, or by using other site-specific approaches that may be more accurate.

EQUATION 6.19 (NEW)
ESTIMATE OF THE FRACTION OF MASS OF BY-PRODUCT K EMITTED FROM PROCESS P FROM TOOLS EQUIPPED WITH EMISSIONS CONTROL EQUIPMENT

$$a_{k,p} = \sum_{i} \frac{n_{k,p,a}}{n_{k,p}}$$

Where:

$a_{k,p}$ = estimate of the fraction of by-product k emitted from process tools running process type p and equipped with suitable emissions control technologies, site-specific fraction

$n_{k,p,a}$ = number of process tools running process type p (emitting by-product k) that are equipped with suitable emissions control technologies, site-specific

$n_{k,p}$ = total number of process tools running process type p and emitting by-product k, site-specific

i = input gas

k = by-product gas

p = process type

Finally, inventory compilers should calculate, for each reporting site, the average uptime of all emissions control systems connected to process tools running process type p (UT_p), using Equation 6.20. To this end, inventory compilers should account for the total time ($Td_{n,p}$) that any emissions control system n connected to process tool(s) running process type p in the reporting facility is not in operational mode when at least one of the manufacturing tools connected to emissions control system n is in operation, and the total time ($TT_{n,p}$) in which emissions control system n has at least one associated manufacturing tool in operation. For determining the amount of tool operating time, inventory compilers may assume that tools that were installed for the whole of the year were operated for 525,600 minutes per year. For tools that were installed or uninstalled during the year, inventory compilers should prorate the operating time to account for the days in which the tool was not installed and treat any partial day that a tool was installed as a full day (1,440 minutes) of tool operation. For an emissions control system that has more than one connected tool, the tool operating time is 525,600 minutes per year if at least one tool was installed at all times throughout the year. For tools that are idle with no gas flown through the tool for part of the year, inventory compilers may calculate total tool time using the actual time that gas is flowing through the tool. Inventory compilers should also note that UT_p may be set to one (1) if suitable backup emissions control equipment or interlocking with the process tool is implemented for each emissions control system. Thus, using interlocked process tools or backup emissions control systems reduces uncertainty by eliminating the need to estimate UT for the reporting facility.

EQUATION 6.20 (NEW)
UPTIME OF EMISSIONS CONTROL SYSTEMS

$$UT_p = 1 - \frac{\sum_n Td_{n,p}}{\sum_n TT_{n,p}}$$

Where:

UT_p = average uptime of all emissions control systems connected to process tools running process type p, site-specific fraction

$Td_{n,p}$ = total time that emissions control system n connected to process tools running process type p in the facility is not in operational mode when at least one of the manufacturing tools connected to emissions control system n is in operation, minutes per year

$TT_{n,p}$ = total time during which emissions control system n has at least one associated manufacturing tool running process type p in operation, minutes per year

n = emissions control system

P = process type

ADAPTING TIER 2 METHODS TO ACCOUNT FOR TECHNOLOGICAL CHANGES

Given the rapid pace of technological change in electronics manufacturing, Tier 2 default emission factors may need to be supplemented or updated in order to remain representative of industry emission rates. A change in any of the following parameters can result in the Tier 2 default emission factors becoming unrepresentative:

- Substrate type (e.g. Si, SiC, or glass) and size (e.g., moving to 450 mm wafers in semiconductor manufacturing);

- Use of a new gas in an existing process type (i.e. in-situ plasma cleaning, remote plasma cleaning, or in-situ thermal cleaning; etching; thin film deposition process) or use of a new process type;
- Film type introduced after 2018;
- Tool platform introduced by a supplier after 2018 or those introduced earlier but used for a new process type;
- Use of new input process GHGs, use of new combinations of process greenhouse gases, or use of low- or no-GWP materials that have the potential to form GHG by-products.

If default emission factors are not available under Tier 2 (e.g., a new gas or process type is introduced), facilities can estimate emissions using Tier 2 and assume a default emission factor (1-U) = 0.8 with by-product emission factors of 0.15 for CF_4 and 0.05 for C_2F_6.[7] Alternatively, facilities can undertake process emissions characterization under Tier 3a and use a hybrid method. A hybrid method would involve applying the Tier 2 defaults to processes and technologies that have not changed while applying Tier 3a site-specific emission factors to processes and technologies that have changed. It is *good practice* to undertake process emissions characterization and use a hybrid method when the new gas and process type combination accounts for 1 percent or more of facility GHG consumption by mass and results in estimated emissions of more than 500 $mtCO_2e$, based on the 0.8, 0.15, and 0.05 default emission factors above.

It is *good practice* for inventory compilers to work with electronics manufacturers to periodically assess whether Tier 2 defaults remain representative of manufacturing conditions, considering the criteria above. If the Tier 2 defaults are found not to be representative in one or more respects, inventory compilers should work with electronics manufacturers to encourage use of hybrid Tier 2 and Tier 3a methods, or to develop country-specific default emission factors that reflect the applicable technological and process changes cited above. Any country-specific default emission factors should represent the full range of processes in the country for each process type, including not only the emission factors for the new or changed processes, but also emission factors for previously existing processes that are still used. Most countries are likely to find it challenging to develop robust, representative country-specific emission factors, and technological changes in a particular country are likely to quickly diffuse into other countries. Thus, it is generally preferable to refine default emission factors at the global rather than at the country level. In this context, facilities are encouraged to report measured emission factors to the IPCC Emission Factor Database (EFDB) in a transparent manner through a process allowing protection of the underlying confidential nature of the information.

Figure 6.2. Decision tree to determine need for measured emission factors, should be used to determine when Tier 3a measured emission factors may be necessary to supplement Tier 2 default emission factors.

In the case where a new substrate type or size will be used in a facility (e.g., 450 mm wafers), emission factors may be measured and applied in phases. For example, in the first year of operation of the 450 mm fab, 300 mm Tier 2c default factors could be used to estimate emissions. In subsequent years, Tier 2 defaults should be used to estimate emissions for up to 50 percent of total gas used in year 2; 25 percent in year 3; 10 percent in year 4; and 0 percent in year 5. See the discussion of the Tier 3a method below for criteria to prioritize these measurements. Once measurements of the 450 mm processes are complete, inventory compilers should work with semiconductor manufacturers to recalculate emissions from years 1-4 to ensure time series consistency.

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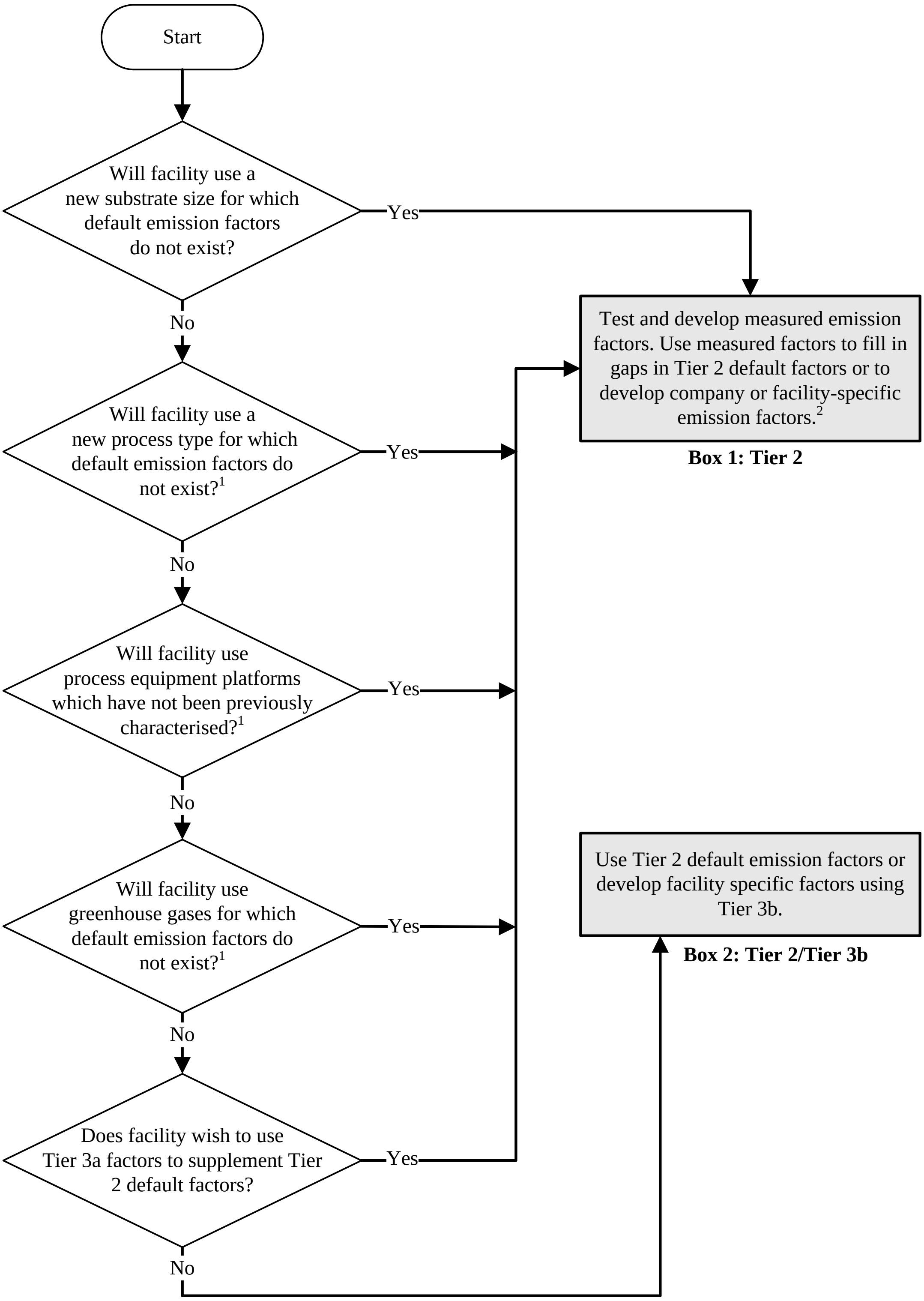
[7] These defaults assume that all of the input gas is either emitted or converted into CF_4 or C_2F_6. In the majority of cases where emission factor data are available, both CF_4 and C_2F_6 are emitted as by-products. The default (1-U) is conservatively based on the least efficient (1-U) for etch or wafer cleaning processes (0.8 for C_2F_6 in Table 6.10). Due to a generally higher CF_4 by-product emission factor for most input gas/process combinations, the majority (75 percent) of the remaining mass is assigned to CF_4 and the rest to C_2F_6.

Figure 6.2 (New) Decision tree to determine need for measured emission factors



Note:

1. If a new gas and process combination are used that accounts for less than 1 percent of facility fluorinated GHG consumption by mass and (1-U) is not measured or not listed, compiler may assume (1-U) = 0.8, B_{CF4} = 0.15, B_{C2F6} = 0.05.

2. Mechanism to submit Tier 3a data to EFDB is still to be designed at the time of writing of this *2019 Refinement*.

TIER 3 METHODS – SITE-SPECIFIC PARAMETERS

Tier 3a – Measured process-specific parameters

The Tier 3a method can be applied to all sub-sectors covered in Chapter 6 (semiconductor, display, PV and MEMS) and uses the same set of equations as the Tier 2c method; however, Tier 3a uses measured values for parameters in Equations 6.13 to 6.20 (see Table 6.3 for details). As discussed earlier, Tier 3a measured emission factors may be used to supplement Tier 2 default factors where some, but not all, processes and technologies have changed. Tier 3a can also be undertaken to develop facility-specific emission factors for broader application in the facility. For example, a facility may have abatement efficiencies that are different from the default DRE values for emission control systems installed on a certain subset of process tools, or may account for emissions from a particular recipe or technology that is more efficient or that may have been developed for the purpose of reducing emissions. Note that in the case of a comprehensive technology change, such as the adoption of a new substrate size (e.g., 450 mm in semiconductor industry), the Tier 3a method would be broadly applied.

For the Tier 3a method, the $(1\text{-}U_{i,p})$ and $B_{k,i,p}$ emission factors in Equations 6.13 to 6.15 and 6.18 to 6.19 are measured for recipes or for families of similar recipes. Thus, the main distinction between the Tier 3a method and the Tier 2c method is that, for the Tier 3a method, p in Equations 6.13 to 6.20 is to be interpreted as meaning a 'recipe' or a family of similar recipes. A recipe can be defined as a specific combination of process conditions (input gas type and flows, plasma power, pressure, temperature, duration, etc.) and technologies used to etch patterns onto electronics devices, to clean film deposition chambers, or to deposit films on substrates. A centreline recipe can be used to establish Tier 3a emission factors for a recipe and each family of similar recipes. Recipes are deemed 'similar' when the centreline process can reasonably be deemed representative of facility-specific process conditions despite potential variability of such process conditions around the centreline process during normal manufacturing operations, and when the substrate size, process type, tool platform and process chamber, film type (SiO_x, SiO_xN_y, Si_xN_y, W, etc.), and input process gas(es) are the same. However, even when similar recipes are grouped, it may not be practicable or economically feasible to implement the Tier 3a methodology across all families of similar recipes or across the many emissions control systems that may be used in a particular electronics manufacturing facility. For this reason, it is *good practice* for facilities undertaking a more comprehensive Tier 3a approach to prioritize testing as follows:

1. Recipe families with highest GHG usage (e.g., chamber cleans) and/or expected emissions should be tested first (e.g., testing should account for the top 75 percent of total process greenhouse gas usage in kg and the top 50 percent of emissions in kg CO_2e.).
2. Stable processes which do not change from wafer to wafer or run to run should have higher priority than processes that change frequently.

Whenever Tier 3a measurements are made, the reporting facility should document the following:

- Date measurements were made;
- Industry sub-sector;
- Substrate size;
- Process type;
- Film type;
- Tool manufacturer, platform and model/chamber name;
- Input gases;
- Process conditions (gas flows, pressure, temperature, power, duration, etc.);
- Input gas emission factors;
- By-product emission factors;
- Fluorine mass balance closure;
- Measurement protocol used.

In addition, facilities using the 3a approach should document all facility-specific process emission factors or emissions control equipment DREs that have been measured by the reporting facility, document which recipes are deemed similar to the measured centreline process, use the measured Tier 3a factors for all similar recipes, and be able to demonstrate to a reasonable degree of certainty that the Tier 3a approach does lead to increased accuracy in reporting emissions. When facility-specific emission factors or destruction removal efficiencies have been measured for a particular recipe or for a family of similar recipes and for a particular emissions control technology or emissions control system, it is NOT *good practice* to revert to default Tier 2 emission factors when such default emission factors are more favourable than the corresponding measured Tier 3a factors as such practice would result in knowingly underestimating emissions.

Tier 3b method—Stack testing

The Tier 3b method may be applied to all sub-sectors covered in Chapter 6 (semiconductor, display, PV and MEMS). Stack testing measures the amount of greenhouse gases emitted from a specific facility through stack systems. A stack system is considered to be one or more stacks that are connected by a common header or manifold, through which an FC- or N_2O-containing gas stream originating from one or more processes is, or has the potential to be, released to the atmosphere. Stack testing is a method commonly used by electronic devices manufacturing facilities to quantify emissions and demonstrate compliance for regulated pollutants used in manufacturing, such as acid gases (e.g., hydrogen fluoride, hydrogen chloride, fluorine, nitric acid, ammonia) and volatile organic compounds (VOCs). The individual process chamber operations that use greenhouse gases, as is the case with acid gases and VOCs, are conducted as batch processes. The fact that they are run concurrently, in rapid succession on a large number of tools which are exhausted to typically a relatively small number of stacks, leads to the expectation that the emissions will largely emulate a continuous process.

The analytical methods available for measuring greenhouse gas emissions from facility stack systems are Fourier Transform Infrared spectroscopy (FTIR) and gas chromatography followed by mass spectrometry (GC/MS). In the case of FTIR, the analytical instrument is brought to the stack system for in-situ analysis. In the case of the GC/MS approach, stack emission samples are collected using sample containers and transported to a laboratory for analysis.

Stack testing may be used to develop site-specific emission factors. The stack method may not be appropriate for facilities with many stacks, frequent changes in production technology or product mix, or an inability to track gas use during testing or emissions control equipment uptime during testing. It is important to perform stack testing when production levels in the fab are representative of year-round production, and when emissions control system uptime is representative of year-round uptime.

Testing Frequency

It is *good practice* for reporting facilities to test all stack systems at the reporting facility that have the potential to emit greenhouse gases in the first year of testing. Typically, this means all acid and caustic/alkali stack systems at the facility should be tested because these are generally the stack systems connected to processes using FC compounds in a fab. It is also important to test all stacks on relevant stack systems during the first year of testing to determine that there are negligible differences in flow or concentration between these stacks. If a facility determines that no substantive changes have occurred in the year following a stack test, the emission factors determined may remain unchanged and retesting is not required; however, stack testing should occur every 3 years at a minimum. In subsequent years, reporting facilities may consider less frequent testing for stack systems that comprise less than 10 percent of total process GHG emissions (expressed in CO_2e). In addition, facilities with a highly variable product mix should consider undertaking annual testing for the first three years to assess the impact that the changing product mix has on their measured emission factors. For all facilities, the following are considered to be substantive changes, and testing should be undertaken in the subsequent year after a stack test if any of the following are met:

(i) If annual consumption, in terms of CO_2e, for any individual FC gas compared with the total of all FC gases changes by more than 10 percentage points from the most recent emissions test. For example, if the use of a single gas converted to CO_2e goes from 25 percent of total gas consumption to greater than 35 percent of total gas consumption, a retest would be triggered for the subsequent year.

(ii) Annual consumption of an FC that was not used during the emissions test or that is not included in the facility-specific emission factor rises to 5 percent (expressed in CO_2e) of the annual consumption of the fab.

(iii) A change by more than 20 percent in the fraction of process tools equipped with emissions control systems, compared to the fraction during the most recent emissions test.

(iv) A change in the substrate size manufactured by the facility since the most recent emissions test.

Stack test method

For each stack system in the reporting facility for which testing is required, inventory compilers should measure the emissions of each FC gas and N_2O from the stack system by conducting an emission test using the methods mentioned in Table 6.14, or their equivalents. In addition, inventory compilers should measure the facility-specific emissions and consumption of each FC and N_2O according to the following steps:

- Measure total gas flow rate up the stack on the test day using EPA Method 1 or 2 or an equivalent method.
- Measure process GHG concentrations of designated gases from relevant stacks using an analytical method with demonstrated accuracy. The analytical method should be validated using US EPA Method 320 or an equivalent validation method.
- Emissions testing should be conducted during a period of 8 hours or longer per stack system while the facility is operating at a representative level with representative emissions control system uptime. Representative in this case means that normal process tools' or emissions control systems' maintenance is being performed during the stack emissions test and that processes running during the test are indicative of normal facility operations.
- Measurements should be taken for all FC gases known to be used by the facility and any possible FC gas by-products. It is recommended measurements be taken for CF_4, C_2F_6, C_3F_8, C_4F_8, C_5F_8, CHF_3, CH_2F_2, and CH_3F as these gases may be formed as by-products.
- The amount of each FC and N_2O gas consumed by each facility during the sampling period should be determined. Where starting and ending gas container pressures are used to estimate consumption, appropriate adjustments for temperature and deviations from ideal gas law behaviour should be made (e.g., by applying the Redlich, Kwong, Soave equation of state with appropriate values for each FC gas and N_2O). Because stack testing is conducted over a relatively brief period, measurements and calculations of gas consumption during that period should be precise to ensure that the resulting emission factors are accurate.
- If consumption of an FC gas is too low to be accurately measured during the testing period, then in order to account for usage, the testing period should be increased or consumption from pro-rated long-term consumption data may be calculated for the testing period.

Inventory compilers should calculate the emissions of each FC gas and N_2O consumed as an input gas using Equation 6.21 and each FC gas formed as a by-product using Equation 6.22. If a stack system is comprised of multiple stacks, inventory compilers should sum the emissions from each stack in the stack system when using Equation 6.21 or Equation 6.22.

EQUATION 6.21 (NEW)
TOTAL GHG INPUT GAS EMITTED FROM STACK SYSTEM DURING SAMPLING PERIOD

$$ES_{i,s} = MW_i \bullet Q_s \bullet \frac{1}{SV} \bullet \frac{1}{10^3} \bullet \sum_{m=1}^{N} \frac{X_{i,s,m}}{10^9} \bullet \Delta t_m$$

Where:

$ES_{i,s}$ = emissions of input gas i from stack system s during the sampling period, kg

MW_i = molecular weight of gas i , g/g-mole

Q_s = flow rate of stack system s during the sampling period, m^3/min.

SV = standard molar volume of gas, 0.0240 m^3/g-mole at 68°F and 1 atm.

$X_{i,s,m}$ = average concentration of input gas i in stack system s during time interval m, ppbv

Δt_m = length of time interval m in the FTIR sampling period, minutes. Each time interval in the FTIR sampling period should be less than or equal to 60 minutes (for example an 8-hour sampling period would consist of at least 8-time intervals).

$1/10^3$ = conversion factor, 1 kilogram/1,000 grams

i = input gas

s = stack system

N = total number of time intervals m in sampling period

m = time interval

EQUATION 6.22 (NEW)

TOTAL FC BY-PRODUCT EMITTED FROM STACK SYSTEM DURING SAMPLING PERIOD

$$ES_{k,s} = MW_k \bullet Q_s \bullet \frac{1}{SV} \bullet \frac{1}{10^3} \bullet \sum_{m=1}^{N} \frac{X_{k,s,m}}{10^9} \bullet \Delta t_m$$

Where:

$ES_{k,s}$ = emissions of by-product k emitted from stack system s during the sampling period, kg

MW_k = molecular weight of by-product gas k, g/g-mole

Q_s = flow rate of stack system s during the sampling period, m 3/min

SV = standard molar volume of gas, 0.0240 m 3/g-mole at 68 °F and 1 atm.

$X_{k,s,m}$ = average concentration of by-product k in stack system s during time interval m, ppbv

Δtm = length of time interval m in the FTIR sampling period, minutes. Each time interval in the FTIR sampling period should be less than or equal to 60 minutes (for example an 8-hour sampling period would consist of at least 8-time intervals).

$1/10^3$ = conversion factor, 1 kilogram/1,000 grams

k = by-product gas

s = stack system

N = total number of time intervals m in sampling period

m = time interval

When calculating emissions, inventory compilers should use the following guidance and the accompanying requirements of recognized maximum field detection limits (FDLs) as detailed in Table 6.15. Field detection limits for instrumentation used in stack testing should not exceed those depicted in Table 6.15

a. If an FC gas or N_2O is consumed during the sampling period, but its emissions are not detected, the ½ FDL value determined for the target compound should be used for the value of $X_{i,s,m}$ in Equation 6.21 .

b. If an FC gas or N_2O is consumed during the sampling period but only detected intermittently during the sampling period, the detected concentration should be used for the value of $X_{i,s,m}$ in Equation 6.21 when available, and a concentration corresponding to one-half of the FDL determined for the target compound should be used for the value of $X_{i,s,m}$ when the target compound is not detected.

c. If an FC gas is not consumed during the sampling period, is not detected during the sampling period, but is an expected by-product, a concentration corresponding to one-half of the FDL determined for the target compound should be used for the value of $X_{k,s,m}$ in Equation 6.22. Expected by-products are CF_4, C_2F_6, CHF_3, CH_2F_2, and CHF_3.

d. If an FC gas or N_2O is not consumed during the sampling period, is not detected during the sampling period, and is not an expected by-product listed in c above, then inventory compilers may assume that emissions for the target compound for the tested stack system are zero.

After calculating $ES_{i,s}$ and $ES_{k,s}$, inventory compilers should calculate a facility-specific emission factor for each input gas consumed (in kg of FC gas or N_2O emitted per kg of input gas i consumed) in the tools that vent to stack systems that are tested, as applicable, using Equation 6.23 of this section. If the emissions of input gas i exceed the consumption of input gas i during the sampling period, then inventory compilers should set $E_{i,s}$ equal to the consumption of input gas i and treat the difference between the emissions and consumption of input gas i as a by-product of the other input gases, using Equation 6.24 of this section.

EQUATION 6.23 (NEW)
GAS SPECIFIC EMISSION FACTOR FOR INPUT GAS

$$EF_{i,f} = \frac{\sum_s ES_{i,s}}{Activity_{i,f} \bullet (UT_f + \frac{1-UT_f}{1-(a_{i,f} \bullet d_i)})}$$

Where:

$EF_{i,f}$ = emission factor for input gas i and facility f representing 100 percent emissions control system uptime, kg emitted per kg of input gas consumed

$ES_{i,s}$ = emissions of input gas i from stack system s during the sampling period, kg

$Activity_{i,f}$ = consumption of input gas i for facility f during the sampling period, kg

UT_f = total uptime of all emissions control systems for facility f during the sampling period, as calculated in Equation 6.30, site-specific fraction

$a_{i,f}$ = estimate of the fraction of gas i emitted from process tools equipped with suitable emissions control technologies for facility f, site-specific fraction, as determined in Equation 6.10

d_i = Destruction Removal Efficiency (DRE) for gas i, fraction

i = input gas

s = stack system

f = facility

After calculating $EF_{i,f}$, inventory compilers should calculate a facility-specific emission factor for each FC by-product k (in kg of by-product k per kg of total FC input gases i consumed) in the tools vented to stack systems that are tested, as applicable, using Equation 6.24 of this section. When calculating the by-product emission factor for an FC input gas i for which emissions exceeded its consumption, inventory compilers should exclude the consumption of that input gas from the term $\sum Activity_{i,f}$.

EQUATION 6.24 (NEW)
FC BY-PRODUCT SPECIFIC EMISSION FACTOR

$$EF_{k,f} = \frac{\sum_s ES_{k,s}}{\sum_i Activity_{i,f} \bullet (UT_f + \frac{1-UT_f}{1-(a_{k,f} \bullet d_k)})}$$

Where:

$EF_{k,f}$ = emission factor for FC by-product gas k emitted from facility f, representing 100 percent emissions control system uptime, kg emitted per kg of all FC input gases i consumed

$ES_{k,s}$ = emissions of FC by-product gas k, emitted from stack system s during the sampling period, kg

$Activity_{i,f}$ = consumption of FC input gas i for facility f during the sampling period, kg

UT_f = total uptime of all emissions control systems for facility f during the sampling period, as calculated in Equation 6.30, site-specific fraction. If the stack system does not have emissions control systems on the tools vented to the stack system, the value of this parameter is zero

$a_{k,f}$ = estimate of the fraction of by-product emitted from process tools equipped with suitable emissions control technologies for facility f, site-specific fraction, as determined in Equation 6.11

d_k = Destruction Removal Efficiency (DRE) for FC by-product k, fraction

i = FC input gas

k = FC by-product gas

s = stack system

f = facility

After calculating $EF_{i,f}$, inventory compilers should calculate annual facility-level emissions of each input gas i consumed during the year using Equation 6.25.

EQUATION 6.25 (NEW)
ANNUAL EMISSION OF INPUT GAS I

$$EA_{i,f} = EF_{i,f} \bullet C_{i,f} \bullet UT_f + \frac{EF_{i,f}}{1 - a_{i,f} \bullet d_i} \bullet C_{i,f} \bullet (1 - UT_f)$$

Where:

$EA_{i,f}$ = annual emissions of input gas i from the stack systems that are tested for facility f, kg/year

$EF_{i,f}$ = emission factor for input gas i and facility f representing 100 percent emissions control system uptime, as calculated in Equation 6.26, kg emitted per kg of input gas consumed

$C_{i,f}$ = total consumption of input gas i for facility f for the reporting year, kg/year

UT_f = the total uptime of all emissions control systems for facility f, during the reporting year, as calculated using Equation 6.27 of this section, site-specific fraction

$a_{i,f}$ = estimate of the fraction of gas i emitted from process tools equipped with suitable emissions control technologies, site-specific fraction, as determined in Equation 6.10 for facility f

d_i = Destruction Removal Efficiency (DRE) for gas i, fraction

i = input gas

f = facility

After calculating $E_{i,f}$, inventory compilers should calculate annual facility-level emissions of each FC by-product k formed using Equation 6.26 of this section.

EQUATION 6.26 (NEW)
ANNUAL EMISSION OF FC BY-PRODUCT K

$$EA_{k,f} = EF_{k,f} \bullet \sum_i C_{i,f} \bullet UT_f + \frac{EF_{k,f}}{1 - a_{k,f} \bullet d_k} \bullet \sum_i C_{i,f} \bullet (1 - UT_f)$$

Where:

$EA_{k,f}$ = annual emissions of FC by-product k from the stack systems that are tested for facility f, kg/year

$EF_{k,f}$ = emission factor for FC by-product gas k, emitted from facility f representing 100 percent emissions control system uptime, as calculated in Equation 6.27 of this section, kg emitted/kg of all FC input gases consumed

$C_{i,f}$ = total consumption of FC input gas i for facility f for the reporting year, kg

UT_f = the total uptime of all emissions control systems for facility f, during the reporting year as calculated using Equation 6.27 of this section, fraction

$a_{k,f}$ = estimate of the fraction of FC by-product gas k emitted from process tools equipped with suitable emissions control technologies, site-specific fraction, as determined in Equation 6.11 for facility f

d_k = Destruction Removal Efficiency (DRE) for FC by-product gas k, fraction

i = FC input gas

k = FC by-product gas

f = facility

Finally, inventory compilers should calculate, for each reporting site, the average uptime of all emissions control equipment connected to process tools for facility f (UT_f), using Equation 6.27. To this end, inventory compilers should account for the total time ($Td_{n,f}$) that any emissions control equipment n connected to process tool(s) in reporting facility f is not in operational mode when at least one of the manufacturing tools connected to emissions control equipment n is in operation, and the total time ($TT_{n,f}$) in which emissions control equipment n has at least one associated manufacturing tool in operation. For determining the amount of tool operating time, inventory compilers may assume that tools that were installed for the whole of the year were operated for 525,600 minutes per year. Inventory compilers should adjust the total minutes to reflect sampling time for the purposes of Equation 6.23 and Equation 6.24. For tools that were installed or uninstalled during the year, inventory compilers should prorate the operating time to account for the days in which the tool was not installed and treat any partial day that a tool was installed as a full day (1,440 minutes) of tool operation. For an emissions control equipment that has more than one connected tool, the tool operating time is 525,600 minutes per year if at least one tool was installed at all times throughout the year. For tools that are idle with no gas flown through the tool for part of the year, inventory compilers may calculate total tool time using the actual time that gas is flowing through the tool. Inventory compilers should also note that UT_f may be set to one (1) if suitable backup emissions control equipment or interlocking with the process tool is implemented for each emissions control system. Thus, using interlocked process tools or backup emissions control systems reduces uncertainty by eliminating the need to estimate UT for the reporting facility. Facility records such as maintenance records for emissions control systems can also be used to estimate emissions control system uptime.

EQUATION 6.27 (NEW)
AVERAGE EMISSIONS CONTROL SYSTEM UPTIME

$$UT_f = 1 - \frac{\sum_n Td_{n,f}}{\sum_n TT_{n,f}}$$

Where:

UT_f = the average uptime factor for all emissions control systems in fab f, fraction. When this term is used for Equation 6.23 and 6.24, evaluate Td_{pf} and UT_{pf} for the sampling period

$Td_{n,f}$ = the total time, in minutes, that emissions control system n, connected to process tool(s) in fab f, is not in operational mode

$TT_{n,f}$ = total time, in minutes per year or in minutes of sampling time when used with Equations 6.25 and 6.26, in which the tool(s) connected at any point during the year to emissions control system n, in fab f could be in operation

n = emissions control system

f = facility

6.2.1.2 FLUORINATED LIQUIDS

Fluorinated liquids are used as HTFs for temperature control, device testing, cleaning substrate surfaces and other parts, and soldering in certain types of electronics manufacturing production processes. Leakage and evaporation of these fluids during use is a source of fluorinated greenhouse gas emissions.

Fluorinated liquid emissions consist primarily of hydrofluoroethers, perfluoropolyethers (including PFPMIE) and other fully fluorinated liquids (perfluorinated amines and perfluoroalkylmorpholines). With the exception of the hydrofluoroethers, all of these compounds are very long-lived in the atmosphere and have high GWPs (near 10,000). It should be noted that some lower GWP fluorinated liquids have been marketed in recent years for some applications, but that such materials may be regulated in some regions (e.g. as volatile organic compounds), and this should be considered when choosing alternative fluorinated liquids. Table 6.5 lists fluorinated liquids that are commonly used in the electronics industry, along with their 100-year GWPs. Note that the list of fluorinated liquids in Table 6.5 is not exhaustive and that additional fluorinated liquids may be used.

TABLE 6.5 (NEW)
FLUORINATED LIQUIDS COMMONLY USED IN THE ELECTRONICS INDUSTRY

Chemical Type	Fluorinated Liquid	AR4 or AR5 100-year GWP[1]
PFPMIE Distillates	PFPMIE fractions, boiling points 55-270 °C (Solvay Galden™ HT series, HT-55 through HT-270)	10,300[2]
	PFPMIE fractions, boiling points 200-230 °C (Solvay Galden™ LS series, LS-200 through LS-230)	10,300[2]
	PFPMIE fractions, boiling points 240-260 °C (Solvay Galden™ HS series, HS-240 through HS-260)	10,300[2]
	PFPMIE fractions, boiling points 81-230 °C (Solvay Galden™ DET, D02, D02-TS, D03, and D05)	10,300[2]
	PFPMIE fractions, boiling points 55-135 °C (Solvay Galden™ SV series, SV-55 through SV-135)	10,300[2]
	PFPMIE fractions (Solvay Galden™ Perfluorosolv series)	10,300[2]
Other Fully Fluorinated Liquids	Perfluorotripropylamine (PTPA, 3M™ Fluorinert™ FC-3283/FC-8270)	Not available[3]
	Perfluorotributylamine (PTBA, 3M™ Fluorinert™ FC40/FC-43)	Not available[3]
	Perfluoroisopropylmorpholine (3M™ Fluorinert™ FC-770)	Not available[3]
	Perfluoromethylmorpholine (3M™ Fluorinert™ FC-3284)	Not available[3]
PFCs[4]	C_6F_{14} (Perfluorohexane, 3M™ Fluorinert™ FC-72)	9,300
	C_7F_{16} (Perfluoroheptane, 3M™ Fluorinert™ FC-84)	7,820
	C_8F_{18} (Perfluorooctane, 3M™ Fluorinert™ FC-3255, FC-104)	7,620
	Blend of C_8F_{18} and perfluoro-2-butyltetrahydrofuran (3M™ Fluorinert™ FC-77)	Not available[3]
Saturated HFCs[4]	HFC-4-3-10mee (Chemours Vertrel™ XF)	1,640
	Blends including HFC-43-10mee and/or other saturated HFCs (Chemours Vertrel™ MCA, SDG, SMT, and SFR)	Approximately 150 to 1,000
Hydrofluoroethers	Methoxytridecafluoroheptene alone (Chemours Opteon™ SF10) and blended with trans-1,2-dichloroethylene (Chemours Opteon™ SF79)	Not available[5]
	HFE-347mcc3 (3M™ Novec™ 7000 Engineered Fluid)	575
	HFE-449s1 (3M™ Novec™ HFE-7100)	297
	HFE-569sf2, (3M™ Novec™ HFE-7200)	59
	1 1 1 2 2 3 4 5 5 5-decafluoro-3-methoxy-4-trifluoromethyl-pentane (3M™ Novec™ HFE-7300)	Not available[6]
	3-ethoxy-1,1,1,2,3,4,4,5,5,6,6,6-dodecafluoro-2-trifluoromethyl-hexane (3M™ Novec™ HFE-7500)	Not available[6]
	Blends including HFE-449s1 and HFE-569sf2 (3M™ Novec™ 71DA, 71DE, 71IPA, 72DA, 72DE, 72FL Engineered Fluids)	41-284
Fluorinated Ketones	perfluoro(2-methyl-3-pentanone) (3M™ Novec™ 649 Engineered Fluid/3M™ Novec™ 1230 Fire Protection Fluid, FK 5-1-12	0.1

TABLE 6.5 (NEW) (CONTINUED)
FLUORINATED LIQUIDS COMMONLY USED IN THE ELECTRONICS INDUSTRY

[1] The GWP in the Fourth Assessment Report (AR4) is provided if the compound has a GWP in AR4. Otherwise, the GWP in the Fifth Assessment Report (AR5) is provided.

[2] This is the GWP for the PFPMIE distillate fraction that is sold under the name Solvay Galden HT-70 (Young et al). Solvay has stated that the HT, LS, HS, SV, and Perfluorosolv series, as well as DET, D02, D02-TS, D03, and D05, have similar chemical structures (varying only in their chain lengths) and are manufactured with the same production process. They differ in their molecular weights because they are different fractions of the source "bulk fluid."

[3] The GWPs for these compounds have not been published in the peer-reviewed literature. However, evaluations by the manufacturer indicate that their GWPs are near 10,000 (US Federal Register Volume 78, Issue 66 (April 5, 2013), pp. 20632-37). This is expected given that these compounds are both fully fluorinated and saturated, as are, for example, the PFCs listed above. The US EPA assigns a default 100-year GWP of 10,000 to compounds that are both saturated and fully fluorinated and that do not have chemical-specific GWPs in either the Fourth or the Fifth Assessment Reports.

[4] In addition to the PFCs and HFCs listed here, some facilities reporting emissions under the US EPA Greenhouse Gas Reporting Program have reported emissions of SF_6 and low-boiling point PFCs and HFCs that are used as heat transfer fluids.

[5] The US EPA estimates a 100-year GWP for methoxytridecafluoroheptene of 2.5 (US Federal Register Volume 80, page 42058, July 16, 2015) and a 100-year GWP for trans-1,2-dichloroethylene of less than five due to its structure and brief atmospheric lifetime (US Federal Register Volume 81, page 32241, May 23, 2016).

[6] The GWPs for these compounds have not been published in the peer-reviewed literature. However, based on their similarity to HFEs for which GWPs have been published (saturated HFEs and HCFEs with 3 or more carbon-hydrogen bonds), the US EPA assigns a default 100-year GWP of 270 to these compounds.

There are two methods for estimating emissions from the use of fluorinated liquids. The choice of methods will depend on the availability of inventory data on the use of fluorinated liquids and is outlined in the decision tree (see Figure 6.3, Decision Tree for Estimation of FC Emissions from Fluorinated Liquids, and see Section 1.5 of Chapter 1, Choosing between the Mass Balance and Emission Factor Approach).

TIER 1 – FLUORINATED LIQUIDS

Tier 1 is appropriate when company-specific data are not available on the consumption of fluorinated liquids. Tier 1 factors are available for semiconductor manufacturing (including both factors for heat transfer fluid applications and for testing, packaging and soldering) and for display (for heat transfer fluid applications). It is the less accurate of the two methods for estimating emissions from losses of fluorinated liquids. The method, unlike the Tier 2 method, gives estimates of emissions for three fluorinated liquids that represent the three main types of compounds used as heat transfer fluids globally (see Table 6.18). For any class of electronic products (semiconductor, MEMS, display), the default emission factors are multiplied by the annual production, P. For fluorinated heat transfer fluid applications, P is the area of substrate processed in units of square meters (m^2). For testing, packaging and soldering, P is the number of packaged devices in thousands (kpcs). The result is a set of annual emissions estimates expressed in kg of materials emitted during the manufacture of a particular class of electronic products. The Tier 1 method for estimating emissions from fluorinated liquids is analogous to the Tier 1 method for estimating greenhouse gas emissions during electronic devices manufacturing. The formula is shown in Equation 6.28.

EQUATION 6.28 (UPDATED)
TIER 1 METHOD FOR ESTIMATION OF TOTAL FC EMISSIONS FROM FLUORINATED LIQUIDS

$$FC_i = EF_i \bullet P$$

Where:

FC_i = emissions of fluorinated liquid i, kg

EF_i = emission factor for fluorinated liquid aggregate emissions either per m^2 of substrate consumed during the period (kg/m^2, for heat transfer fluid applications), or per thousand packaged devices, kg/kpcs, for testing, packaging and soldering

P = annual production either in m^2 of substrate used during the production of electronic devices, including test substrates (for heat transfer fluid applications), or in thousands of packaged devices (for testing, packaging and soldering). If annual production in m^2 is not available from an electronics producer, P in m^2 may be calculated as the product of the annual manufacturing capacity and annual plant production capacity utilisation (fraction) of that producer.

For semiconductor manufacturing, it is *good practice* to apply equation 6.28 twice—once to estimate emissions of fluorinated liquids from heat transfer fluid applications and again to estimate emissions of fluorinated liquids from testing, packaging, and soldering—and then to sum the results of both calculations to obtain total emissions of fluorinated liquids. Tier 1 factors for fluorinated liquids are not available for PV. Tier 1 factors are also not available for substrate cleaning. Thus, the Tier 2 approach should be used to estimate fluorinated liquid emissions from these sources.

TIER 2 METHOD – FLUORINATED LIQUIDS

There is one Tier 2 method for estimating actual emissions from the use of any and each fluorinated liquid, applicable to all electronics manufacturing sub-sector (semiconductor, display MEMS, PV) and to each application (temperature control, device testing, cleaning substrate surfaces and other parts, and soldering). This method is a mass-balance approach that accounts for fluorinated liquid usage over an annual period. This Tier 2 method is appropriate when company-specific data are available; it is the only method applicable to the use of fluorinated liquids for cleaning substrates surfaces and other parts, and for the PV sub-sector. Over the course of a year, fluorinated liquids are used to fill newly purchased equipment and to replace fluorinated liquid loss from equipment operation through evaporation. Inventory compilers should provide the chemical composition of the fluid(s) for which emissions are estimated for each application. The method is expressed in Equation 6.29.

EQUATION 6.29 (UPDATED)
TIER 2 METHOD FOR ESTIMATION OF FC EMISSIONS FROM FLUORINATED LIQUIDS

$$FC_i = \rho_i \bullet \left(I_{i,t-1} + P_{i,t} - N_{i,t} + R_{i,t} - I_{i,t} - D_{i,t}\right)$$

Where:

FC_i = emissions of fluorinated liquid i, kg

ρ_i = density of fluorinated liquid i, kg/litre

i = fluorinated liquid

$I_{i,\,t-1}$ = inventory of liquid FC_i in containers other than equipment at the beginning of the reporting year, litres in stock or storage. The inventory at the beginning of the reporting year should be the same as the inventory at the end of the previous year

$P_{i,t}$ = acquisitions of liquid FC_i during the reporting year, including amounts purchased from chemical suppliers, amounts purchased from equipment suppliers with or inside of equipment, and amounts returned to the facility after off-site recycling, litres

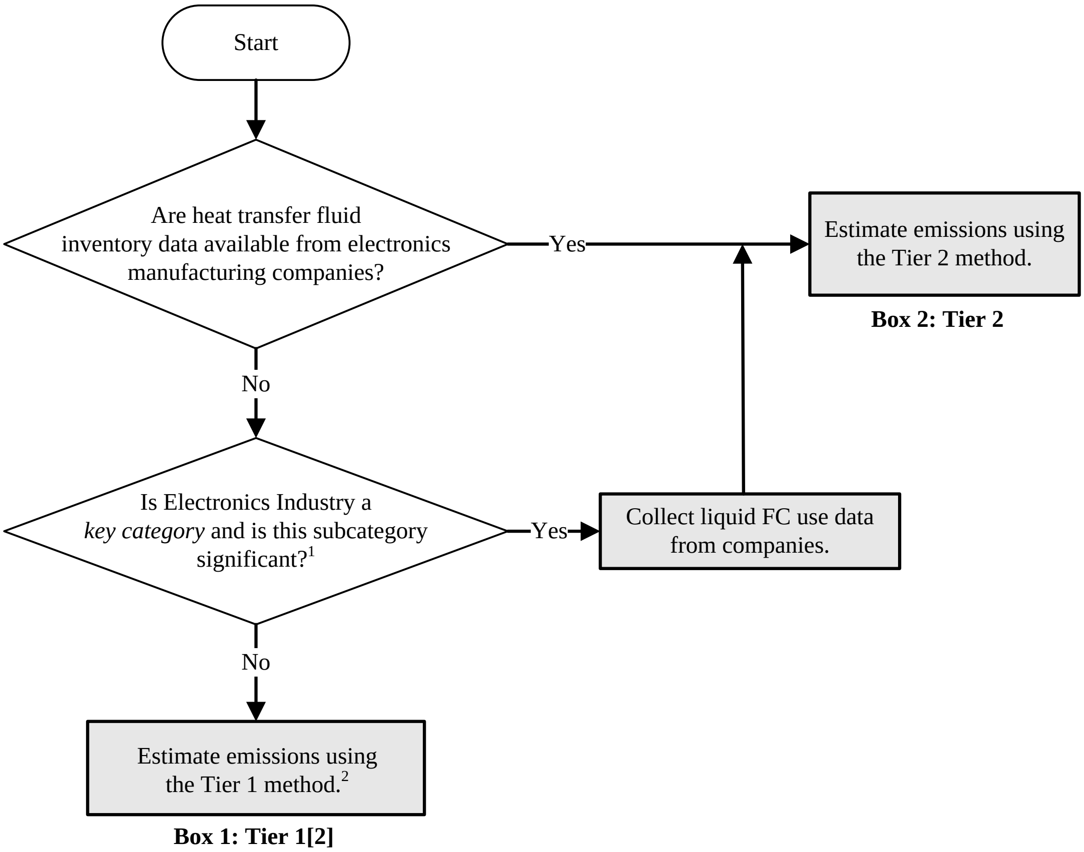
$N_{i,t}$ = total nameplate capacity (full and proper charge) of equipment that uses fluorinated liquid i and that is newly installed in the reporting facility during the reporting year, litres

$R_{i,t}$ = total nameplate capacity (full and proper charge) of equipment that uses fluorinated liquid i and that is removed from service in the reporting facility during the reporting year, litres

$I_{i,t}$ = inventory of liquid FC_i in containers other than equipment at the end of the reporting year, litres in stock or storage

$D_{i,t}$ = disbursements of fluorinated liquid i, including amounts returned to chemical suppliers, sold with or inside of equipment, and sent off-site for verifiable recycling or destruction, litres. Disbursements should include only amounts that are properly stored and transported so as to prevent emissions in transit

Figure 6.3 (Updated) Decision tree for estimation of emissions from fluorinated liquids loss from electronics manufacturing



Note:

1. See Volume 1 Chapter 4, Methodological Choice and Identification of Key Categories (noting Section 4.1.2 on limited resources), for discussion of *key categories* and use of decision trees.
2. Substrate cleaning (any sub-sector) and any application in the PV sub-sector require use of Tier 2 method.

6.2.2 Choice of emission factors

This section provides the default emission factors that should be used for reporting emissions under the Tier 1 and Tier 2 methods. Please refer to the corresponding emission factor tables (Tables 6.6 to 6.13 and Tables 6.17 and 6.18) for each method.

The main sources of default emission factors are the U.S. EPA Greenhouse Gas Reporting Rule (GHGRP, 40 U.S. Code of Federal Regulations (CFR) part 98; Subpart I), the *2006 IPCC Guidelines* (Volume 3, Chapter 6), the World Semiconductor Council (2011, 2012, 2014 and 2016), the World Display device Industry Cooperation Committee, and industry surveys conducted during the *2019 Refinement*.

In the case where a new input gas is used for which no default emission factor (1-U_i) has been established, facilities can estimate emissions using the Tier 2 methods and assume a default emission factor of (1-U_i) = 0.8 with by-product emission factors of $B_{CF4,i}$=0.15 and $B_{C2F6,i}$=0.05. However, this provision could lead to incomplete and inaccurate results if the use of the new chemical leads to the formation of by-products other than CF_4 and C_2F_6 or if the default emission factors fail to accurately represent actual emissions from the new gas or process. Thus, reporters should measure the emission factors for the new gas or process and use a partial Tier 3a method to account for emissions resulting from the use of the new chemical or new process if the consumption of the new gas exceeds 1 percent of the facility's GHG consumption by mass.

6.2.2.1 GASEOUS FLUORINATED COMPOUNDS AND NITROUS OXIDE

TIER 1

The default emission factors for the Tier 1 method are presented in Table 6.6 below. Because the Tier 1 default emission factors for the semiconductor sector in Table 6.6 are based on a 50/50 split between 200mm and 300mm production, it is *good practice to use* the Tier 1 default emission factors for the semiconductor sector that are available in the *2006 IPCC Guidelines* in cases where the wafer size produced is known to be 200 mm or smaller.

In using Tier 1, it is not *good practice* to modify, in any way, the set of greenhouse gases or the values of the emission factors assumed in Table 6.6. For any given electronics manufacturing facility, inventory compilers should not combine emissions estimated using the Tier 1 method with emissions estimated using the Tier 2 or 3 methods. For example, inventory compilers may not use the Tier 1 factor for CF_4 to estimate the emissions of CF_4 from semiconductors and combine it with the results of other gases from a Tier 2 or Tier 3 method. It should also be noted that the Tier 1 emission factors presented in Table 6.6 should not be used for any purpose other than estimating annual process gas-aggregate emissions from semiconductor, display, MEMS, or PV manufacturing for compilation of the national greenhouse gas inventory. Tier 1 emissions for the semiconductor sub-sector are calculated based on the surface area of wafer produced. Display emissions are calculated based on the surface area of input glass corresponding to array processes, i.e. the processes used to manufacture the thin film transistors that are part of the display devices. Note that the array input glass area is different than the input glass area used for the manufacturing of colour filters used in display devices, which does not involve the use (or emissions) of fluorinated GHGs. Also note that the Tier 1 factors for MEMS are highly uncertain due to the fact that they were generated from a limited data set. Additionally, as previously discussed in the Choice of Method section, the high Tier 1 emission factor for SF_6 corresponds to a MEMS-specific process consisting of etching vias through the substrate, a process which consumes significant amounts of SF_6.

TABLE 6.6 (UPDATED)
TIER 1 GAS-SPECIFIC EMISSION FACTORS FOR PROCESS GHG EMISSIONS FROM ELECTRONICS MANUFACTURING

Electronics industry subsector	CF_4	C_2F_6	C_3F_8	C_4F_6	c-C_4F_8	C_4F_8O	C_5F_8	CHF_3	CH_2F_2	NF_3	SF_6	N_2O
Semiconductors, kg/m^2	0.36	0.12	0.03	0.003	0.01	7E-5	0.001	0.05	0.003	0.15	0.05	1.01
Display, g/ array input glass area m^2	0.65				0.001			0.0024		1.29	4.14	17.06
PV, g/m^2	5	0.2										
MEMS, kg/m^2	0.015				0.076						1.86	

Sources:

The Tier 1 emission factors for the display sub-sector were provided by the World Display device Industry Cooperation Committee.

The Tier 1 emission factors for the semiconductor sub-sector were provided by the World Semiconductor Council. The factors are based on seven years of data collected by the regions comprising the World Semiconductor Council (WSC), i.e. China, Chinese Taipei, Europe, Japan, Korea, and the United States. Included is data for facilities operated by WSC companies outside the WSC regions e.g., Singapore. The factors are calculated starting from the purchased quantities of the listed gases and by considering the emission factors reported in the Table 6.6 for Tier 2a, including the formation of by-products. The emissions calculated in this way have then been divided by the total area of silicon produced. As the Tier 2a default emission factors used to develop the Tier 1 default emission factors for the semiconductor sector in Table 6.5 assumed a 50/50 split between 200mm and 300mm production, it is *good practice to use* the Tier 1 default emission factors for the semiconductors sector that are available in the *2006 IPCC Guidelines* in cases where the wafer size produced is known to be 200 mm or smaller.

TIER 2

The default emission factors for the Tier 2 methods are presented in Tables 6.7 to 6.13 and Table 6.17 below.

Note that F_2 and COF_2 are included in the list of input gases for the Tier 2 methods because these gases are known to be used for TFD chamber cleaning and because the use of F_2 and COF_2 for chamber cleaning can lead to the formation of CF_4 and other high-GWP by-products, but no data was available to derive emission factors for these gases. Note also that, although COF_2 is a known by-product of chamber cleaning processes using fluorinated carbon gases (e.g. CF_4, C_2F_6, etc.), no by-product factor for COF_2 (i.e. $B_{COF2,i}$) was included in the Tier 2 default tables dues to the low GWP (~1) and short atmospheric life of COF_2.

TABLE 6.7 (UPDATED)
TIER 2A METHOD – DEFAULT EMISSION FACTORS FOR GHG EMISSIONS FROM SEMICONDUCTOR MANUFACTURING AND FROM MEMS MANUFACTURING UNDER CERTAIN CONDITIONS**

Process Gas	**CF_4**	**C_2F_6**	**C_3F_8**	**C_3F_8 Remote**	**C_4F_6**	**c-C_4F_8**	**C_4F_8O**	**C_5F_8**	**CHF_3**	**CH_2F_2**	**CH_3F**	**C_2HF_5**	**NF_3 Remote**	**NF_3**	**SF_6**	**N_2O TFD**	**N_2O other**	**COF_2**	**F_2**
(1-U_i)	0.73	0.55	0.4	0.063	0.15	0.13	0.14	0.085	0.47	0.2	0.35	0.064	0.02	0.18	0.55	0.78	1.0	NM	NM
B_{CF4}	NA	0.19	0.2	NA	0.06	0.099	0.13	0.053	0.082	0.061	0.028	0.077	0.034	0.067	0.12	NA	NA	NM	NM
B_{C2F6}	0.043	NA	0.000018	NA	0.063	0.02	0.045	0.047	0.045	0.044	0.01	0.024	NA	0.014	0.095	NA	NA	NM	NM
B_{C3F8}	NA	NA	NA	NA	NA	NA	NA	0.000055	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_{C4F6}	0.00060	NA	NA	NA	NA	0.0015	NA	NA	0.000032	NA	0.0011	NA	NA	NA	NA	NA	NA	NA	NA
B_{C4F8}	0.0014	NA	NA	NA	0.0051	NA	NA	NA	0.00021	0.071	0.0065	NA	NA	NA	NA	NA	NA	NA	NA
B_{C5F8}	0.00045	NA	NA	NA	NA	0.0035	NA	NA	0.00079	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_{CH3F}	0.0021	NA	0*	NA	0.00064	0.0004	NA	NA	0.0043	0.0043	NA	NA	NA	0.0022	0.0009	NA	NA	NA	NA
B_{CH2F2}	0.0057	NA	NA	NA	0.00003	0.00026	NA	NA	0.00082	NA	0.0021	NA	NA	0.00023	0.0000021	NA	NA	NA	NA
B_{CHF3}	0.040	0.002	0.0000012	NA	0.018	0.022	NA	0.0053	NA	0.057	0.015	NA	NA	0.0068	0.0014	NA	NA	NA	NA

Source: Data collected under the U.S. EPA Greenhouse Gas Reporting Rule (GHGRP, 40 U.S. Code of Federal Regulations (CFR) part 98; Subpart I)

*<10^{-7}

** Tier 2a default factors for semiconductor manufacturing may be applied to MEMS manufacturing processes that are carried out using semiconductor manufacturing tools when such MEMS processes are similar to semiconductor manufacturing processes (for further details see discussion in the Choice of method section, in particular footnote 3).

NA = Not Applicable; NM = Not Measured (but known to occur). If a new gas and process combination are used that accounts for less than 1 percent of facility fluorinated GHG consumption by mass and (1-U) is NM or not listed, compiler may assume (1-U) = 0.8, B_{CF4} = 0.15, B_{C2F6} = 0.05.

TABLE 6.8 (NEW)
TIER 2A AND 2B METHODS -- DEFAULT WEIGHTING FACTORS γ_i AND γ_k FOR SEMICONDUCTOR AND MEMS MANUFACTURING UNDER CERTAIN CONDITIONS*

Tier, input gas (γ_i) vs. by–product (γ_k), and wafer size	**Gamma weighting factors by gas and chamber cleaning process type combination**				
	CF_4 (IPC+ITC)/EWC	**C_2F_6 IPC/EWC**	**c-C_4F_8 IPC/EWC**	**NF_3 (IPC+ITC)/EWC**	**SF_6 IPC/EWC**
Tier 2a					
γ_i	13.3†	9.3	4.7	14.5†	10.7
γ_k	7.7	2.6	NA	NA	NA
Tier 2b					
γ_i (≤200 mm wafer size)	13.3†	9.3	4.7	2.9†	10.7
γ_k (≤200 mm wafer size)	12.1†	2.6	NA	NA	NA
γ_i (300 mm wafer size)	NA	NA	NA	26.0†	NA
γ_k (300 mm wafer size)	3.2†	NA	NA	NA	NA

Source: Survey of industrial facility data conducted by the authors of Chapter 6.

*Gamma weighting factors for semiconductor manufacturing may be applied to MEMS manufacturing processes that are carried out using tools and processes similar to those used to manufacture semiconductors (for further details see discussion in the Choice of method section, in particular footnote 3).

† The gamma values for 200 mm were developed based on IPC only and the values for 300 mm were developed based on both ITC and IPC. Gamma is assigned based on analogy due to similar emission factors for IPC and ITC, where known, for the same gas and wafer size. For all other cases where no gamma is provided, compiler may assume γ_i = 10, γ_k = 10.

TABLE 6.9 (NEW)
TIER 2B METHOD – DEFAULT EMISSION FACTORS FOR GHG EMISSIONS FROM SEMICONDUCTOR MANUFACTURING AND FROM MEMS MANUFACTURING UNDER CERTAIN CONDITIONS*

Process Gas	**CF_4**	**C_2F_6**	**C_3F_8**	**C_3F_8 Remote**	**C_4F_6**	**$c\text{-}C_4F_8$**	**C_4F_8O**	**C_5F_8**	**CHF_3**	**CH_2F_2**	**CH_3F**	**C_2HF_5**	**NF_3 Remote**	**NF_3**	**SF_6**	**N_2O TFD**	**N_2O other**	**COF_2**	**F_2**
≤200 mm wafer size																			
$(1-U_i)$	0.79	0.55	0.4	NA	0.12	0.12	0.14	0.072	0.51	0.13	0.7	0.064	0.028	0.18	0.58	1.0	1.0	NM	NM
B_{CF4}	NA	0.19	0.2	NA	0.1	0.11	0.13	NA	0.085	0.079	NA	0.077	0.015	0.11	0.13	NA	NA	NM	NM
B_{C2F6}	0.03	NA	NA	NA	0.11	0.019	0.045	0.014	0.035	0.025	0.0034	0.024	NA	0.0059	0.11	NA	NA	NM	NM
B_{C3F8}	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_{C5F8}	0.00077	NA	NA	NA	NA	0.00043	NA	NA	0.0012	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_{CHF3}	0.059	0.002	NA	NA	0.066	0.02	NA	0.0039	NA	0.049	NA	NA	NA	NA	0.0011	NA	NA	NA	NA
300 mm wafer size																			
$(1-U_i)$	0.65	0.8	0.3	0.063	0.15	0.18	NA	0.1	0.38	0.2	0.32	NA	0.018	0.18	0.29	0.5	1.0	NM	NM
B_{CF4}	NA	0.21	0.21	NA	0.059	0.046	NA	0.11	0.075	0.06	0.031	NA	0.038	0.04	0.034	NA	NA	NM	NM
B_{C2F6}	0.061	NA	0.18	NA	0.062	0.028	NA	0.083	0.067	0.044	0.011	NA	NA	0.02	0.041	NA	NA	NM	NM
B_{C3F8}	NA	NA	NA	NA	NA	NA	NA	0.00012	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_{C4F6}	0.0015	NA	NA	NA	NA	0.008	NA	NA	0.0001	NA	0.0012	NA	NA	NA	NA	NA	NA	NA	NA
B_{C4F8}	0.0033	NA	NA	NA	0.0051	NA	NA	NA	0.00067	0.072	0.007	NA	NA	NA	NA	NA	NA	NA	NA
B_{CH3F}	0.0053	NA	0.00073	NA	0.00065	0.0022	NA	NA	0.037	0.0044	NA	NA	NA	0.0036	0.0082	NA	NA	NA	NA
B_{CH2F2}	0.014	NA	NA	NA	0.00003	0.0014	NA	NA	0.0026	NA	0.0023	NA	NA	0.00039	0.00002	NA	NA	NA	NA
B_{CHF3}	0.013	NA	0.012	NA	0.017	0.03	NA	0.0069	NA	0.057	0.016	NA	NA	0.011	0.0039	NA	NA	NA	NA

Source: Data collected under the U.S. EPA Greenhouse Gas Reporting Rule (GHGRP, 40 U.S. Code of Federal Regulations (CFR) part 98; Subpart I)

* Tier 2b default factors for semiconductor manufacturing may be applied to MEMS manufacturing processes that are carried out using semiconductor manufacturing tools when such MEMS processes are similar to semiconductor manufacturing processes (for further details see discussion in the Choice of method section, in particular footnote 3).

NA = Not Applicable; NM = Not Measured (but known to occur). If a new gas and process combination are used that accounts for less than 1 percent of facility fluorinated GHG consumption by mass and (1-U) is NM, compiler may assume (1-U) = 0.8, B_{CF4} = 0.15, B_{C2F6} = 0.05.

TABLE 6.10 (NEW)
TIER 2C METHOD (≤200 MM) – DEFAULT EMISSION FACTORS FOR GHG EMISSIONS FROM SEMICONDUCTOR MANUFACTURING AND FROM MEMS MANUFACTURING UNDER CERTAIN CONDITIONS*

Process Gas	**CF_4**	**C_2F_6**	**C_3F_8**	**C_4F_6**	**c-C_4F_8**	**C_4F_8O**	**C_5F_8**	**CHF_3**	**CH_2F_2**	**CH_3F**	**C_2HF_5**	**NF_3**	**SF_6**	**N_2O TFD**	**N_2O other**	**COF_2**	**F_2**
Etching or Wafer Cleaning (EWC)																	
$(1-U_i)$	0.73	0.72	NA	0.12	0.14	NM	0.0722	0.51	0.13	0.7	0.064	0.19	0.55	NA	NA	NM	NM
B_{CF4}	NA	0.1	NA	0.13	0.11	NM	NA	0.085	0.079	NA	0.077	0.004	0.13	NA	NA	NM	NM
B_{C2F6}	0.046	NA	NA	0.11	0.037	NM	0.014	0.035	0.025	0.0034	0.024	0.025	0.11	NA	NA	NM	NM
B_{C5F8}	0.0012	NA	NA	NA	0.0086	NA	NA	0.0012	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_{CHF3}	0.09	0.047	NA	0.066	0.04	NA	0.0039	NA	0.049	NA	NA	NA	0.0012	NA	NA	NA	NA
Remote Plasma Cleaning (RPC)																	
$(1-U_i)$	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.028	NA	NA	NA	NA	NA
B_{CF4}	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.015	NA	NA	NA	NA	NA
In-situ Plasma Cleaning (IPC)																	
$(1-U_i)$	0.92	0.55	0.4	NA	0.1	0.14	NA	NA	NA	NA	NA	0.18	NM	NA	NA	NM	NA
B_{CF4}	NA	0.21	0.2	NA	0.11	0.13	NA	NA	NA	NA	NA	0.14	NM	NA	NA	NM	NA
B_{C2F6}	NA	NA	NA	NA	NA	0.045	NA	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA
Thin Film Deposition (TFD)																	
$(1-U_i)$	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1.0	NA	NA	NA
Other																	
$(1-U_i)$	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1.0	NA	NA

Source: Data collected under the U.S. EPA Greenhouse Gas Reporting Rule (GHGRP, 40 U.S. Code of Federal Regulations (CFR) part 98; Subpart I)

* Tier 2c default factors for semiconductor manufacturing may be applied to MEMS manufacturing processes that are carried out using semiconductor manufacturing tools when such MEMS processes are similar to semiconductor manufacturing processes (for further details see discussion in the Choice of method section, in particular footnote 3).

NA = Not Applicable; NM = Not Measured (but known to occur). No emission factor data was available for in-situ thermal cleaning for ≤200 mm, but the process is known to be used. If a new gas and process combination are used that accounts for less than 1 percent of facility fluorinated GHG consumption by mass and (1-U) is NM, compiler may assume (1-U) = 0.8, B_{CF4} = 0.15, B_{C2F6} = 0.05.

TABLE 6.11 (NEW)
TIER 2C METHOD (300 MM) – DEFAULT EMISSION FACTORS FOR GHG EMISSIONS FROM SEMICONDUCTOR MANUFACTURING AND FROM MEMS MANUFACTURING UNDER CERTAIN CONDITIONS*

Process Gas	**CF_4**	**C_2F_6**	**C_3F_8**	**C_4F_6**	**c-C_4F_8**	**C_5F_8**	**CHF_3**	**CH_2F_2**	**CH_3F**	**NF_3**	**SF_6**	**N_2O TFD**	**N_2O other**	**COF_2**	**F_2**
Etching and Wafer Cleaning (EWC)															
(1-U_i)	0.65	0.8	0.3	0.15	0.18	0.1	0.38	0.2	0.32	0.16	0.29	NA	NA	NM	NM
B_{CF4}	NA	0.21	0.21	0.059	0.046	0.11	0.075	0.06	0.031	0.045	0.034	NA	NA	NM	NM
B_{C2F6}	0.061	NA	0.18	0.062	0.028	0.083	0.067	0.044	0.011	0.045	0.041	NA	NA	NM	NM
B_{C3F8}	NA	NA	NA	NA	NA	0.00012	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_{C4F6}	0.0015	NA	NA	NA	0.0083	NA	0.0001	NA	0.0012	NA	NA	NA	NA	NA	NA
B_{C4F8}	0.0033	NA	NA	0.0051	NA	NA	0.00067	0.072	0.007	NA	NA	NA	NA	NA	NA
B_{CH3F}	0.0053	NA	0.00073	0.00065	0.0022	NA	0.037	0.0044	NA	0.008	0.0082	NA	NA	NA	NA
B_{CH2F2}	0.014	NA	NA	0.00003	0.0014	NA	0.0026	NA	0.0023	0.00086	0.00002	NA	NA	NA	NA
B_{CHF3}	0.013	NA	0.012	0.017	0.03	0.0069	NA	0.057	0.0016	0.025	0.0039	NA	NA	NA	NA
Remote Plasma Cleaning (RPC)															
(1-U_i)	NA	NA	0.063	NA	NA	NA	NA	NA	NA	0.018	NA	NA	NA	NA	NA
B_{CF4}	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.038	NA	NA	NA	NA	NA
In-situ Plasma Cleaning (IPC)															
(1-U_i)	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.2	NA	NA	NA	NA	NA
B_{CF4}	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.037	NA	NA	NA	NA	NA
In-situ Thermal Cleaning (ITC)															
(1-U_i)	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.28	NA	NA	NA	NA	NA
B_{CF4}	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.01	NA	NA	NA	NA	NA

TABLE 6.11 (NEW) (CONTINUED)
TIER 2C METHOD (300 MM) – DEFAULT EMISSION FACTORS FOR GHG EMISSIONS FROM SEMICONDUCTOR MANUFACTURING AND FROM MEMS MANUFACTURING UNDER CERTAIN CONDITIONS*

Process Gas	**CF_4**	**C_2F_6**	**C_3F_8**	**C_4F_6**	**c-C_4F_8**	**C_5F_8**	**CHF_3**	**CH_2F_2**	**CH_3F**	**NF_3**	**SF_6**	**N_2O TFD**	**N_2O other**	**COF_2**	**F_2**
TFD															
(1-U_i)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.5	NA	NA	NA
Other															
(1-U_i)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1.0	NA	1.0

Source: Data collected under the U.S. EPA Greenhouse Gas Reporting Rule (GHGRP, 40 U.S. Code of Federal Regulations (CFR) part 98; Subpart I)

* Tier 2c default factors for semiconductor manufacturing may be applied to MEMS manufacturing processes that are carried out using semiconductor manufacturing tools when such MEMS processes are similar to semiconductor manufacturing processes (for further details see discussion in the Choice of method section, in particular footnote 3).

NA = Not Applicable; NM = Not Measured (but known to occur). If a new gas and process combination are used that accounts for less than 1 percent of facility fluorinated GHG consumption by mass and (1-U) is NM, compiler may assume (1-U) = 0.8, B_{CF4} = 0.15, B_{C2F6} = 0.05.

Table 6.12 (Updated)
Tier 2c method – default emission factors for GHG emissions from Display manufacturing

Process Gas	CF_4	$c\text{-}C_4F_8$	CHF_3	NF_3	SF_6	N_2O
Etching						
$(1-U_i)$	0.6	0.1	0.2	0.11	0.3	NA
B_{CF4}	NA	0.009	0.07	NA	NA	NA
B_{C2F6}	NA	NA	0.05	NA	NA	NA
B_{CHF3}	NA	0.02	NA	NA	NA	NA
Remote plasma cleaning (RPC)						
$(1-U_i)$	NA	NA	NA	0.03	NA	NA
In-situ plasma cleaning (IPC)						
$(1-U_i)$	NA	NA	NA	0.3	0.9	NA
Thin film deposition (TFD)						
$(1-U_i)$	NA	NA	NA	NA	NA	0.63

Table 6.13 (Updated)
Tier 2c Method -- Default emission factors for GHG emissions from PV manufacturing

Process Gas (i)	CF_4	C_2F_6	CHF_3	CH_2F_2	C_3F_8	$c\text{-}C_4F_8$	NF_3 Remote	NF_3	SF_6	C_4F_6	C_5F_8	C_4F_8O	F_2	COF_2
Etch 1-Ui	0.7	0.4	0.4	NA	NA	0.2	NA	NA	0.4	NA	NA	NA	NA	NA
TFD 1-Ui	NA	0.6	NA	NA	0.1	0.1	NA	0.3	0.4	NA	NA	NA	NA	NA
Etch B_{CF4}	NA	0.2	NA	NA	NA	0.1	NA	NA	NA	NA	NA	NA	NA	NA
Etch B_{C2F6}	NA	NA	NA	NA	NA	0.1	NA	NA	NA	NA	NA	NA	NA	NA
TFD B_{CF4}	NA	0.2	NA	NA	0.2	0.1	NA	NA	NA	NA	NA	NA	NA	NA

Notes: NA denotes not applicable based on currently available information

Table 6.14 (New)
Methods and procedures for conducting emissions tests for stack systems

For each stack system for which you use Tier 3b method to calculate annual emissions	You should	Using the method cited below or equivalent
For each fluorinated GHG	Measure the concentration in the stack system.	Using U.S. EPA Method 320 at 40 CFR part 63, appendix A or ASTM D6348-03. Conduct the test run for a minimum of 8 hours for each stack system.
	Select sampling port locations and the number of traverse points.	U.S. EPA Method 1 or 1A at 40 CFR part 60, appendix A-1.
	Determine gas velocity and volumetric flow rate.	U.S. EPA Method 2, 2A, 2C, 2D, 2F or 2G at 40 CFR part 60, appendix A-1 and A-2.
	Determine gas molecular weight.	U.S. EPA Method 3, 3A, or 3B at 40 CFR part 60, appendix A-2 using the same sampling site and time as the fluorinated GHG sampling.
	Measure gas moisture content.	U.S. EPA Method 4 at 40 CFR part 60, appendix A-3 or using FTIR.

TABLE 6.15 (NEW)
MAXIMUM FIELD DETECTION LIMITS (FDL) APPLICABLE TO FLUORINATED COMPOUNDS (FC) CONCENTRATION MEASUREMENTS FOR STACK SYSTEMS

Fluorinated GHG Analyte	Maximum Field detection limit (ppbv*)
CF_4	20
C_2F_6	20
C_3F_8	20
C_4F_6	20
$c–C_4F_8$	20
C_5F_8	20
CHF_3	20
CH_2F_2	40
CH_3F	40
NF_3	20
SF_6	4
Other fully fluorinated GHGs	20
Other fluorinated GHGs	40

* ppbv = parts per billion by volume

EMISSIONS CONTROL TECHNOLOGY FACTORS

Since 2006, the performance of emissions control devices in production conditions has been more extensively characterized, and the *2019 Refinement* provides revised default DRE values for a larger basket of gases (see Table 6.17). Figure 6.4 provides guidance for deciding when a particular emissions control technology may be suitable to abate fluorinated compounds (FCs) and N_2O emissions from electronic devices manufacturing, when default emissions control technology factors may be used, or when site-specific destruction removal efficiencies can or should be measured. With regards to emissions control equipment, "exhaust gases" refers to the combination of all gases exiting the process chamber (unreacted precursors plus by-products formed in the process), plus any gases subsequently added such as pump purge gases.

First, in the case of emissions control technologies using hydrocarbon fuel, inventory compilers should consider whether emissions to be abated originate from NF_3- or F_2-based remote plasma clean (RPC) applications (step [1] in Figure 6.4). These processes lead to the formation of significant amounts of molecular fluorine (F_2) originating from the conversion of NF_3 into F_2 or the limited utilization efficiency of F_2 (when the latter is used as a cleaning precursor). When the exhaust gases contain large amounts of F_2 and when hydrocarbon-fuel-based combustion emissions control technology is used, direct reaction with the hydrocarbon fuel and F_2 to form CF_4 can occur.[8,9] Unless the original equipment manufacturer (OEM) or the electronic devices manufacturer can certify that the rate of conversion from F_2 to CF_4 or from NF_3 to CF_4 is <0.1 percent on a mass basis, a default value of $AB_{NF3,CF4} = 0.093$ or $AB_{F2,CF4} = 0.0116$ should be used in Equations 6.7 (Tier 2a/2b) or Equation 6.15 (Tier 2c/3a) to estimate the amount of CF_4 produced within and emitted from the emissions control device (step [2] in Figure 6.4).

Second, inventory compilers should verify whether site-specific emissions control technologies are suitable for the gas to be abated (step [3] in Figure 6.4). In doing so, inventory compilers should consult Table 6.16, where an 'X' indicates which technology is, in principle, capable of abating a certain gas. Definitions of common emissions control technologies are provided in the footnotes of Table 6.16. Note that the absence of an 'X' in Table 6.16 for a particular combination of gas and emissions control technology does not necessarily preclude the ability of the technology to abate a particular gas, but such ability should be supported by experimental data from the original equipment manufacturer (OEM) or the electronic devices manufacturer. Because new emissions control technologies could emerge, a 'T' in last row of Table 6.16 indicates that, to be considered as being suitable for treating a specific gas, the OEM or the electronic devices manufacturer would need to provide testing data to show that, when the new emissions control technology is tested under representative gas flow conditions, defaults (or site-specific) DREs can be achieved using an industry-accepted measurement methodology that accounts for dilution.[10,11,12]

Third, inventory compilers should verify emissions control technologies have been tested and are certified by the OEM(s) to meet the default DRE values indicated in Table 6.17 (step [4] in Figure 6.4). To do so, the reporting facility should define its worst-case scenarios as the highest total FC or N_2O flows through each model of emissions control systems (gas by gas and process type by process type across the facility) and highest total flow scenarios (with N_2 dilution accounted for, see step [6]), and the reporting facility should request the emissions control equipment manufacturer(s) to certify that the default DREs can be met in the worst-case scenarios for each model of emissions control systems. In the case that the OEM(s) cannot certify that the emissions control system(s) can meet the default DRE values of Table 6.17 (step [5] of Figure 6.4), the corresponding DRE value should be set to zero (0 percent), or the reporting facility may set the DRE value using DREs measured by the electronics device manufacturer (site-specific DREs) or certified by the OEM using an industry-accepted measurement methodology for the site-specific worst case scenarios as previously described (OEM certified DREs). If a facility wishes to claim a DRE value higher than the default DRE values of Table 6.17, it should perform site specific testing (step [7] of Figure 6.4). When using site-specific DREs, a suitable DRE testing frequency should be adopted to ensure that at least 5 percent of the installed emissions control equipment population is tested annually for a representative

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[8] Gray, Fraser, and Afroza Banu, "Influence of CH4-F2 mixing on CF4 by-product formation in the combustive abatement of F2," Research Disclosure

[9] Czerniak, Mike, "Mechanisms for PFC Formation in CVD Applications," presented at SESHA 2018

[10] Protocol for Measuring Destruction or removal Efficiency (DRE) of Fluorinated Greenhouse Gas Abatement Equipment in Electronics Manufacturing. United States Environmental Protection Agency. EPA 430-R-10-003 (2010). https://www.epa.gov/sites/production/files/2016-02/documents/dre_protocol.pdf

[11] Guideline for Environmental Characterization of Semiconductor Process Equipment – Revision 2. International SEMATECH Manufacturing Initiative. Technology Transfer #06124825B-ENG (2009). http://www.lexissecuritiesmosaic.com/gateway/FedReg/document_4825beng.pdf

[12] JEITA Guideline for F-GHG Characterization and Management. Japan Electronics and Information Technologies Industries Association (2011). http://semicon.jeita.or.jp/committee/docs/F-GHG_guideline_20110520_en.pdf

sample of process applications. To use OEM-specific DREs, it is *good practice* to state the test conditions and range of input process gas and total gas for which the DRE is applicable.

Fourth, to ensure that DRE values remain accurate, it is essential that facilities ensure that emissions control equipment is installed, maintained and operated per manufacturer's specifications. Proper operation requires all parameters to be within manufacturer's specifications, including items such as vacuum pumps' purges, fuel / oxidizer settings, supply and exhaust flows and pressures, and utilities to the emissions control equipment (fuel gas flow and pressure, calorific value, water quality, flow & pressure, extract flow and pressure, etc.). Please note that not exceeding the emissions control equipment suppliers' maximum flow specifications requires that all gases, including post-process-chamber purges, are taken into account. Also note that some vacuum pumps' purge flow indicators are inaccurate and could deliver higher-than-indicated purge flows, exceeding the emissions control equipment suppliers' maximum flow specifications. Accurate flows can be determined using a calibrated portable mass flow meter (MFM) with a minimum accuracy of +/- 5 percent. It is suggested to perform calibration every time a vacuum pump is serviced or exchanged.

TABLE 6.16 (NEW)
EMISSIONS CONTROL EQUIPMENT SUITABILITY TABLE FOR DESTRUCTION REMOVAL EFFICIENCY (DRE) OF PROCESS GHG EMISSIONS

Emissions Control Equipment Technology	**Process GHG Emission**														
	CF_4	**C_2F_4**	**C_2F_6**	**C_3F_8**	**C_4F_6**	**$c\text{-}C_4F_8$**	**C_4F_8O**	**C_5F_8**	**CHF_3**	**CH_2F_2**	**CH_3F**	**C_2HF_5**	**NF_3**	**SF_6**	**N_2O**
Cartridge (Media consumed)						X			X				X	X	X
Catalyst (Media not consumed)	X												X	X	X
Hot-wet (electrical) < 850° C															
Hot-wet (electrical) > 850° C				X	X	X							X		
Plasma	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Combustion	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
New technology	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T

'X' indicates that the technology is potentially suitable to use the default DRE for the particular gas.

"T" indicates that, to be considered as being suitable for treating a specific gas, the OEM would need to provide testing data to show that, when the new emissions control technology is tested on worst-case gas flow conditions, defaults (or site-specific) DREs can be achieved using an industry-accepted measurement methodology that accounts for dilution.

Emissions Control Equipment technology definitions:

Cartridge – Any form of dry-bed passive gas treatment, either heated or working at ambient-temperature. The active media is consumed by reaction with the target gas.

Catalyst – This includes wet or dry beds, possible heating of the catalyst bed, and possible wet pre- or post-scrubbing. The media is not consumed by reaction with the target gas, it simply reduces the energy barrier of the reaction chemistry.

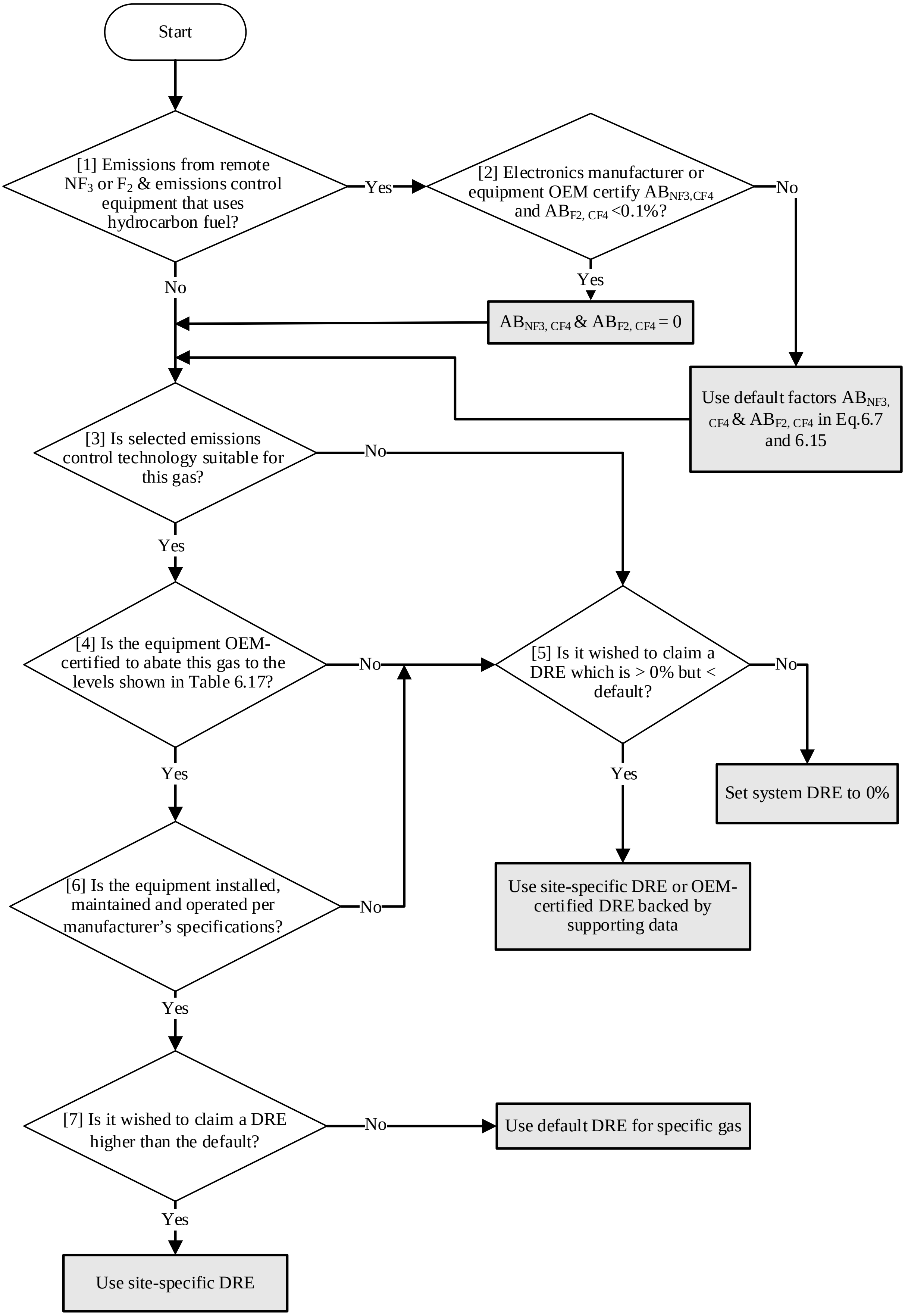
Hot-wet – This includes emissions control equipment described as "thermal wet" and indicates electrical heating followed by wet scrubbing. May also include a pre-wet scrubber.

Plasma – This involves the use of plasmas (e.g. RF, DC, or microwave) operated at atmospheric or sub-atmospheric pressures potentially combined with wet or dry scrubbing of by-products. May also include introduction of water, air, hydrogen and/or oxygen as chemical reagents.

Combustion – This includes all configurations of fuel combustion and reaction zone design, water- or air-cooled, and dry or wet post-scrubbing.

New Technology – This is to account for the possibility of new emissions control technologies emerging that are not included in the categories above.

Figure 6.4 (New) Decision tree for process GHG emission control equipment default emission factors



Note: references to equipment in the above figure mean emission control equipment.

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TABLE 6.17 (UPDATED)
TIER 2 DEFAULT DRE PARAMETERS FOR ELECTRONICS INDUSTRY PROCESS GAS EMISSIONS REDUCTION TECHNOLOGIES (DECIMAL FRACTION)

Process Gas	CF_4	C_2F_4	C_2F_6	C_3F_8	C_4F_6	c-C_4F_8	C_4F_8O (b)	C_5F_8 (a)	CHF_3	CH_2F_2	CH_3F	C_2HF_5 (a)	NF_3	SF_6	N_2O
DRE	0.89	0.96	0.95	0.99	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.95	0.95	0.95	0.60

Source: Data collected under the U.S. EPA Greenhouse Gas Reporting Rule (GHGRP, 40 U.S. Code of Federal Regulations (CFR) part 98; Subpart I) and survey of industrial facility and original equipment manufacturers (OEMs) data conducted by the authors of Chapter 6.

Notes: The average DRE values were derived from individual experimental DRE data points measured under actual or representative production conditions for each specific gas, using industry-accepted measurement protocols.

a) Insufficient data to determine a meaningful average value; analogue used instead (see below)

b) No data available to determine a meaningful average value; analogue used instead (see below)

c) C_4F_8 is used as the analogue for C_5F_8, and C_4F_8O as it has 4-carbon. C_2F_6 is used as the analogue for C_2HF_5 and C_2H_5F as it is linear 2-carbon. For future compounds, apply C_4F_8 for any cyclic compound, and follow linear analogue relative to C for those remaining.

6.2.2.2 FLUORINATED LIQUIDS

TABLE 6.18 (NEW)
TIER 1 DEFAULT EMISSION FACTORS FOR FLUORINATED LIQUIDS

Representative Fluorinated Liquids	Electronics Industry Sector		
	Semiconductor or MEMS heat transfer fluid applications during manufacturing (kg/m^2)	**Semiconductor or MEMS testing, packaging and soldering (kg/kpcs)**	**Display heat transfer fluid applications during manufacturing (kg/m^2)**
HFE-449sl	0.06	1 x 10^{-4}	0.00002
C_6F_{14}	0.07	3 x 10^{-5}	0.00004
PFPMIE	0.04	1 x 10^{-5}	0.00004

Note:

1. The default emission factors for semiconductor manufacturing from heat transfer fluid applications are based on the arithmetic average of the emission factors for the United States, Europe and Taiwan, Province of China. The US emission factors are based on reporting from several manufacturers in 2016. The European emission factors are based on reporting from four facilities, averaged over three years. The Taiwan emission factors are based on reporting from manufacturers representing 95% market share, averaged over five years. For all regions, the number of fluorinated liquids emitted was ten or more; these fluorinated liquids were sorted into three groups of chemically similar fluorinated liquids represented by the fluorinated liquids in the table. HFE-449sl is used to represent hydrofluoroethers; C_6F_{14} is used to represent fully fluorinated liquids manufactured by 3M™; and PFPMIE is used to represent fully fluorinated liquids manufactured by Solvay™.

2. Default emission factors for semiconductor testing, packaging, and soldering are based on reporting by semiconductor manufacturers in Taiwan, Province of China, averaged over three and a half years. These manufacturers represent 80% of the market share in Taiwan, Province of China.

3. The default emission factors for display are based on reporting by display manufacturers in Taiwan, Province of China, averaged over three years. These manufacturers represent 90% of market share in Taiwan, Province of China. The number of fluorinated liquids emitted was seven; these fluorinated liquids were sorted into three groups of chemically similar fluorinated liquids represented by the fluorinated liquids in the table.

4. There is no heat transfer fluid Tier 1 default for PV and thus the only solution for estimating emissions of fluorinated liquids from these subsectors is the Tier 2 method.

5. There is no Tier 1 default for substrate cleaning and, therefore, the Tier 2 method should be used to estimate emissions from this source.

6.2.3 Choice of activity data

Activity data for the electronics industry consists of data on gas consumption and/or production figures (surface area of substrate used during the production of electronic devices, e.g. silicon, glass). For the more data-intensive Tier 2 and Tier 3 methods, gas consumption data is necessary at the facility, substrate-size, process-type, or recipe levels, depending on the Tier. See the guidance regarding the calculation and apportioning of gas consumption under "Choice of Method." For the Tier 1 methods, inventory compilers will need to determine the total surface area of electronic substrates used during the production of electronic devices for a given year. The best sources of either gas usage data or substrate area data are the owners and operators of the electronics manufacturing facilities in each country. However, if it is not possible to obtain the activity data from the owners and operators, Tier 1 estimates may be developed using data on substrate area that is available from purchasable databases. Silicon consumption may be estimated using an appropriate edition of the World Fab Forecast (WFF) database, published quarterly by Semiconductor Equipment & Materials International (SEMI).[13] The database contains a list of plants (production as well as R&D, pilot plants, etc.) worldwide, with information about location, design capacity, wafer size, product type (including MEMS), and more. Other databases are available e.g., IC Insights, Gartner and VLSI.[14, 15, 16] Similarly, SEMI's 'Flat Panel Display Fabs on Disk' database provides an estimate of glass consumption for global TFT-Display manufacturing. IHS provide market data on the Solar/PV and display industries.[17]

Table 6.7 of the *2006 IPCC Guidelines* provided design capacity figures, but these values, which were estimated for 2003 through 2005, are no longer accurate. Table 6.7 is not updated in this *2019 Refinement* because the update would lose its accuracy very quickly given the rapid pace of growth and change in the electronics industry. Nevertheless, the following guidance remains applicable to design capacity data extracted from the purchasable databases above. Note that electronic devices manufacturing plants may not be operated at design capacities for sustained periods, such as a full year, as production typically fluctuates depending on product demand. For semiconductor manufacturing, publicly available industry statistics show that the global annual average capacity utilisation during the period 1991 – 2000 varied between 76 and 91 percent, with an average value of 82 percent and most probable value of 80 percent. When country-specific capacity utilisation data are not available, the suggested capacity utilisation for semiconductor manufacturing is 80 percent, which should be used consistently for a time series of estimates. For display manufacturing, 2016 fab capacity utilisation ranged between 76 and 91 percent.[18] For PV manufacturing, published capacity utilisation data ranges between 77 – 92 percent, with the average for the years 2003 and 2004 of 86 percent. Therefore, 86 percent is the recommended default figure to use for C_u (see Equation 6.1).

When estimating emissions during PV manufacture, one should account for the fraction of the industry that actually employs FCs (F_{PV} in Equation 6.1).

6.2.4 Completeness

Completeness for electronics manufacturing requires accounting for all fluorinated GHGs, N_2O (see section 6.1.1) and fluorinated liquids (see Table 6.5[19]) emitted from all emissions sources (see Table 6.1) at all facilities in all electronics manufacturing subsectors (see Table 6.2) in a country. Complete accounting of emissions from the electronics industry should be achievable in most countries because there are a limited number of companies and plants. Inventory compilers can contact national or international industry associations (e.g., the appropriate national or regional Semiconductor Industry Association) and/or FC suppliers to obtain contact information for electronics manufacturers in their countries. Note that national statistical databases usually do not provide detailed information about electronic devices manufacturing plants, and information about the manufacturing capacities and utilization of such plants is often considered confidential (e.g. actual surface area of substrate used or quantity of final product produced). Nevertheless, commercially-available databases provide facility-specific information

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[13] The term 'fab' is synonymous with clean room/manufacturing facility. Semiconductor and flat panel display manufacturing plants are often called fabrication plants, from which the abbreviation 'fab' follows

[14] http://www.icinsights.com/services/global-wafer-capacity/

[15] https://www.gartner.com

[16] https://www.vlsiresearch.com/

[17] https://technology.ihs.com/

[18] https://electroiq.com/2016/11/display-panel-makers-increase-fab-utilization-rate-to-90-in-q4-2016/.

[19] Note that the list of fluorinated liquids in Table 6.5 is not exhaustive and that additional fluorinated liquids may be used. Thus, for completeness purposes, inventory compilers should check whether any fluorinated liquids other than those listed in Table 6.5 may be used at any particular facility

with production capacity estimates that can be used for the Tier 1 method (see section 6.2.3 "Choice of activity data").

FC Consumption: Generally, electronics devices manufacturers will have good records of consumption of FC gases, N_2O, and fluorinated liquids. In compiling annual consumption of the relevant chemicals, completeness requires that the inventory of gases and fluorinated liquids account for the mass or volume of such chemicals stored in containers at the beginning and at the end of the year, acquisitions during the year through purchases and other transactions, but also transfers of chemicals and of equipment that may contain chemicals, including heels. Also, when apportioning gas consumption between process types, inventory compilers should ensure that the apportioning model does not omit or double count consumption for any particular process type.

By-Product Generation: Completeness also requires tracking emissions of all FC by-products that result from reactions of input gases with each other, with carbon-containing films, and with hydrocarbon fuels. See the guidance on these by-product emissions in section 6.2.2.1.

Fluorinated Liquids: A complete accounting of fluorinated liquids requires accounting for all uses of these liquids in all electronics subsectors in the country. As discussed in section 6.1.1, fluorinated liquids are used to control temperatures during manufacturing, to test devices, for soldering, and for cleaning of substrates and other parts. Because the Tier 1 default emission factors do not cover all of these uses in all subsectors, using the Tier 1 method for fluorinated liquids could affect the completeness of emissions estimates. Specifically, insufficient data was available to devise Tier 1 emission factors for the use of fluorinated liquids in cleaning substrates for all sub-sectors, as well as for heat transfer applications in the PV sub-sector, and for testing, packaging and soldering in the display and PV sub-sectors. Thus, for such applications and sub-sectors, inventory compilers should check whether fluorinated liquids are used at any particular facility, and, to ensure completeness, use only the Tier 2 method in such cases.

Other products, research and development (R&D) and tool commissioning activities: Inventory compilers should be aware that new guidance was added to Volume 3, Chapter 8 of the *2019 Refinement* to account for fluorochemicals emissions used to waterproof electronic circuits. As mentioned above, new products and processes may be introduced from time to time during the course of electronic devices manufacturing, and *good practice* for this industry is to incorporate a mechanism that accounts for reporting the introduction of new products and processes that may affect emissions estimates, and for periodically reporting newly measured emission factors to the IPCC emission factors database (EFDB). Note that it is *good practice* to include gas purchases in support of R&D and tool commissioning activities in the consumption figures used for a particular facility.

6.2.5 Developing a consistent time series

Use of FCs and N_2O 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. Emission factors for the electronics industry have also been revised since the publication of the *2006 IPCC Guidelines* and the consistency of the time series could be improved by applying the revised emission factors to the full time series. The 2019 Tier 2a, 2b or 2c emission factors can be applied to the historical emissions previously calculated with the 2006 Tier 2a or Tier 2b emission factors. For the semiconductor sub-sector, if the wafer size manufactured is not known, 2019 Tier 2a emission factors should be applied to data from 2005 or later. Due to the prevalence of 200 mm or smaller wafer sizes prior to 2005, the 2019 Tier 2b emission factors for 200 mm should be applied to data from 2004 or earlier instead of the Tier 2a emission factors. If historical data are not available to permit use of a Tier 3 or 2 methods, then the Tier 1 method using default emission parameters can be used retrospectively. In this case, it is *good practice* to use the Tier 1 factors from the *2006 IPCC Guidelines* for years through 2010. For 2011 and the following years, it is *good practice* to use the Tier 1 factors from the *2019 Refinement* for most sub-sectors; however, for the semiconductor sub-sector, in cases where it is known that the wafer size manufactured is 200 mm or smaller, it is *good practice* to continue to use the Tier 1 factors from the *2006 IPCC Guidelines*. Both Tier 1 and Tier 2 could then be applied simultaneously for the years in which more data become available to provide a comparison for purposes of splicing the results of the Tier 1 and Tier 2 methods. This should be done according to the guidance provided in Volume 1, Chapter 5.

In order to ensure a consistent emissions record over time, an inventory compiler should recalculate FC and N_2O emissions for all years reported whenever emissions calculation procedures are changed (e.g., if an inventory compiler 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 compiler will need to consider how current plant data can be used to recalculate emissions for these years. It may be possible to apply current facility-specific emission parameters to sales data from previous years, provided that facility 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. If substantial changes have occurred at a facility which prevent full recalculation or new variables are introduced in the equations such as emissions control equipment uptime or apportioning abated gas use to process type, the inventory compiler can apply both the previously used and the new method for at least one year and preferably more to provide a comparison. If the trends observed using this overlap splicing technique are not consistent then use of an alternate technique provided in Volume 1, Chapter 5 should be implemented.

6.3 UNCERTAINTY ASSESSMENT

6.3.1 Emission factor uncertainties

As discussed in the Choice of Method section, the Tier 1 emission factors are expected to be highly uncertain because they do not account for the identities and quantities of the gases actually consumed, for the process types in which those gases are used, for wafer size (for semiconductors), or for the use of emission control systems. A quantitative estimate of the uncertainty of the Tier 1 emission factors (EFs) could not be developed based on the data available, but gas consumption is known to vary widely by device type (e.g., memory vs. logic for semiconductor manufacturing), and gas-specific EFs are known to vary widely by process type, by wafer size and by the fraction of emissions abated. Thus, the Tier 1 method is the least accurate estimation method and should be used only in cases where facility-specific data are not available.

The relative uncertainties at the 95 percent confidence level, estimated for each emission factor of the Tier 2b and 2c methods, are shown in Tables 6.19, and 6.20 for semiconductor manufacturing. It was not possible to estimate the uncertainty of the Tier 2a emission factors for the semiconductor sub-sector and of the Tier 2c emission factors for the display sub-sector due to lack of data. To estimate uncertainties, the relative standard deviations for each Tier 2c entry were first calculated across all experimental data points (measured utilization efficiencies and by-product emission factors) for each particular gas i, process type, and wafer size. The relative standard deviations were then rounded to one significant figure and doubled to estimate uncertainties at the 95 percent confidence level. The same method was used for the Tier 2b entries for each gas and wafer size. The large uncertainties of Tier 2 emission factors are due to the wide distributions of individual experimental emission factors, which depend on process conditions and on the design of the process chambers. Because process conditions such as gas flows, pressure, temperature, or plasma power can vary widely for a particular gas and process chamber design, the utilization efficiencies or by-product emission factors can also significantly change from one process recipe to another, even within a particular process type. Although electronic devices manufacturers can typically run hundreds or even thousands of different recipes (with differing process conditions and manufacturing tool types) – providing an averaging effect over all recipe-specific emission factors –, actual emission factors (for any particular facility) may nevertheless differ from the Tier 2c, 2b, or 2a default emission factors. However, for the Tier 2c method and for some gases, process types, and wafer size combinations, the relatively large number of experimental emission factors taken into account for some combinations (e.g. when more than 20-30 individual experimental factors are averaged to estimate a particular default Tier 2c factor) provides higher confidence that the default can accurately represent actual (facility-specific) emission factors. Because the Tier 2a and Tier 2b methods provide lower resolution than the Tier 2c method (Tier 2a emission factors are only disaggregated by input gas i, and Tier 2b emission factors are only disaggregated by input gas and by wafer size), the overall uncertainty of the Tier 2a and 2b methods can be expected to be higher than for the Tier 2c method.

The impact of the Tier 2 emission factors’ uncertainties on the overall emissions estimate for a particular electronic device manufacturing facility can be estimated by combining the probability distribution functions (PDFs) of the emission factors. Approaches to combine uncertainties include the propagation of error method and Monte Carlo simulations (see Volume 1, Chapter 3 of the *2019 Refinement*). For electronic devices manufacturing, the Monte Carlo approach is suggested because the propagation of error method theoretically requires that the standard deviation divided by the mean value of a variable is less than 0.3, which is often not the case for Tier 2 emission factors (Id.).

Using the Tier 3a method can help significantly reduce reporting uncertainties, even in the case of a hybrid method when a partial Tier 3a method is used in combination with the Tier 2c method. This is because the standard deviations of emission factors for a specific recipe or for a family of similar recipes (Tier 3a factors) can be much lower than those of default Tier 2c factors. Indeed, when running a particular recipe, process conditions such as gas flows, temperature, pressure, or plasma power are tightly controlled, and the substrate-to-substrate variability of emission factors is typically less than 5 percent in terms of relative standard deviations. When using Monte Carlo simulations to estimate the uncertainty of combined Tier 2c / Tier 3a emissions estimates for a particular facility, reporters should use a PDF describing the distribution functions of each Tier 2b or Tier 3a factor and combine such functions to determine the impact of the individual EF uncertainties on the uncertainty of the overall emissions estimate. Normal, lognormal, or other appropriate functions should be used to describe the PDFs of the variables. Then, suitable PDFs should be used to describe the variations of activity data (e.g. heel, input gas consumption, emissions control equipment efficiency – see Section 6.3.2) and such PDFs should be combined with those of the emission factors to estimate the uncertainty of the total emissions calculations.

TABLE 6.19 (UPDATED)
ESTIMATES OF RELATIVE UNCERTAINTIES (%) OF TIER 2B EMISSION FACTORS FOR SEMICONDUCTOR MANUFACTURING, 95 PERCENT CONFIDENCE INTERVALS.

Process Gas	**CF_4**	**C_2F_6**	**C_3F_8**	**C_3F_8 Remote**	**C_4F_6**	**$c\text{-}C_4F_8$**	**C_4F_8O**	**C_5F_8**	**CHF_3**	**CH_2F_2**	**CH_3F**	**C_2HF_5**	**NF_3 Remote**	**NF_3**	**SF_6**	**N_2O TFD**	**N_2O Other**	**COF_2**	**F_2**
≤200 mm wafer size																			
$(1-U_i)$	†	40	†	NA	200	†	†	†	100	160	†	100	200	150	†	NA	NA	NA	NA
B_{CF4}	NA	120	†	NA	200	†	†	NA	80	140	NA	100	180	†	†	NA	NA	NA	NA
B_{C2F6}	400	NA	NA	NA	400	†	†	†	200	120	†	140	NA	†	†	NA	NA	NA	NA
B_{C3F8}	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_{C5F8}	†	NA	NA	NA	NA	†	NA	NA	†	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_{CHF3}	120	†	NA	NA	†	†	NA	†	NA	†	NA	NA	NA	NA	†	NA	NA	NA	NA
300 mm wafer size																			
$(1-U_i)$	60	†	†	†	200	140	NA	180	120	200	140	NA	400	200	140	120	NA	NA	NA
B_{CF4}	NA	†	†	NA	400	200	NA	160	200	200	200	NA	600	†	400	NA	NA	NA	NA
B_{C2F6}	200	NA	†	NA	400	160	NA	200	400	200	200	NA	NA	400	200	NA	NA	NA	NA
B_{C3F8}	NA	NA	NA	NA	NA	NA	NA	†	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_{C4F6}	†	NA	NA	NA	NA	†	NA	NA	†	NA	40	NA	NA	NA	NA	NA	NA	NA	NA
B_{C4F8}	400	NA	NA	NA	†	NA	NA	NA	†	†	†	NA	NA	NA	NA	NA	NA	NA	NA
B_{CH3F}	200	NA	†	NA	†	†	NA	NA	400	†	NA	NA	NA	†	†	NA	NA	NA	NA
B_{CH2F2}	†	NA	NA	NA	†	†	NA	NA	†	NA	†	NA	NA	†	†	NA	NA	NA	NA
B_{CHF3}	200	NA	†	NA	400	200	NA	400	NA	180	200	NA	NA	400	†	NA	NA	NA	NA

† Insufficient data was available to calculate uncertainty.

TABLE 6.20 (UPDATED)
DEFAULT ESTIMATES OF RELATIVE UNCERTAINTIES (%) OF TIER 2C EMISSION FACTORS FOR SEMICONDUCTOR MANUFACTURING (≤200 MM), 95 PERCENT CONFIDENCE INTERVALS

Process Gas	**CF_4**	**C_2F_6**	**C_3F_8**	**C_4F_6**	**$c\text{-}C_4F_8$**	**C_4F_8O**	**C_5F_8**	**CHF_3**	**CH_2F_2**	**CH_3F**	**C_2HF_5**	**NF_3**	**SF_6**	**N_2O TFD**	**N_2O Other**	**COF_2**	**F_2**
Etching or Wafer Cleaning (EWC)																	
$(1\text{-}U_i)$	40	60	NA	200	140	NA	†	100	160	†	100	140	100	NA	NA	NA	NA
B_{CF4}	NA	180	NA	200	200	NA	NA	80	140	NA	100	†	†	NA	NA	NA	NA
B_{C2F6}	400	NA	NA	400	400	NA	†	200	120	†	140	†	†	NA	NA	NA	NA
B_{C5F8}	†	NA	NA	NA	†	NA	NA	†	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_{CHF3}	120	†	NA	†	†	NA	†	NA	†	NA	NA	NA	†	NA	NA	NA	NA
Remote Plasma Cleaning (RPC)																	
$(1\text{-}U_i)$	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	200	NA	NA	NA	NA	NA
B_{CF4}	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	180	NA	NA	NA	NA	NA
In-situ Plasma Cleaning (IPC)																	
$(1\text{-}U_i)$	†	40	†	NA	†	†	NA	NA	NA	NA	NA	180	NA	NA	NA	NA	NA
B_{CF4}	NA	120	†	NA	†	†	NA	NA	NA	NA	NA	†	NA	NA	NA	NA	NA
B_{C2F6}	NA	NA	NA	NA	NA	†	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Thin Film Deposition (TFD)																	
$(1\text{-}U_i)$	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	†	NA	NA	NA
Other																	
$(1\text{-}U_i)$	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	†	NA	NA

† Insufficient data was available to calculate uncertainty.

Table 6.21 (Updated)
Default estimates of relative uncertainties (%) of Tier 2c emission factors for semiconductor manufacturing (300 mm), 95 percent confidence intervals

Process Gas	**CF_4**	**C_2F_6**	**C_3F_8**	**C_4F_6**	**$c\text{-}C_4F_8$**	**C_5F_8**	**CHF_3**	**CH_2F_2**	**CH_3F**	**NF_3**	**SF_6**	**N_2O TFD**	**N_2O Other**	**COF_2**	**F_2**
Etching and Wafer Cleaning (EWC)															
$(1\text{-}U_i)$	60	†	†	200	140	180	120	200	140	180	140	NA	NA	NM	NM
B_{CF4}	NA	†	†	400	200	160	200	200	200	200	400	NA	NA	NM	NM
B_{C2F6}	200	NA	†	400	160	200	400	200	200	200	200	NA	NA	NM	NM
B_{C3F8}	NA	NA	NA	NA	NA	†	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_{C4F6}	†	NA	NA	NA	†	NA	†	NA	40	NA	NA	NA	NA	NA	NA
B_{C4F8}	400	NA	NA	†	NA	NA	†	†	†	NA	NA	NA	NA	NA	NA
B_{CH3F}	200	NA	†	†	†	NA	400	†	NA	†	†	NA	NA	NA	NA
B_{CH2F2}	†	NA	NA	†	†	NA	†	NA	†	†	†	NA	NA	NA	NA
B_{CHF3}	200	NA	†	400	200	400	NA	180	200	200	†	NA	NA	NA	NA
Remote Plasma Cleaning (RPC)															
$(1\text{-}U_i)$	NA	NA	†	NA	NA	NA	NA	NA	NA	400	NA	NA	NA	NA	NA
B_{CF4}	NA	NA	NA	NA	NA	NA	NA	NA	NA	600	NA	NA	NA	NA	NA
In-situ Plasma Cleaning (IPC)															
$(1\text{-}U_i)$	NA	NA	NA	NA	NA	NA	NA	NA	NA	100	NA	NA	NA	NA	NA
B_{CF4}	NA	NA	NA	NA	NA	NA	NA	NA	NA	†	NA	NA	NA	NA	NA
In-situ Thermal Cleaning (ITC)															
$(1\text{-}U_i)$	NA	NA	NA	NA	NA	NA	NA	NA	NA	†	NA	NA	NA	NA	NA
B_{CF4}	NA	NA	NA	NA	NA	NA	NA	NA	NA	†	NA	NA	NA	NA	NA
TFD															
$(1\text{-}U_i)$	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	120	NA	NA	NA

TABLE 6.21 (UPDATED) (CONTINUED)
DEFAULT ESTIMATES OF RELATIVE UNCERTAINTIES (%) OF TIER 2C EMISSION FACTORS FOR SEMICONDUCTOR MANUFACTURING (300 MM), 95 PERCENT CONFIDENCE INTERVALS

Process Gas	**CF_4**	**C_2F_6**	**C_3F_8**	**C_4F_6**	**c-C_4F_8**	**C_5F_8**	**CHF_3**	**CH_2F_2**	**CH_3F**	**NF_3**	**SF_6**	**N_2O TFD**	**N_2O Other**	**COF_2**	**F_2**
Other															
(1-U_i)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	†	NA	NA

† Insufficient data was available to calculate uncertainty.

6.3.2 Activity data uncertainty

Activity data uncertainty originates from multiple variables and particular attention should be taken to minimize the uncertainty and the potential bias of the measurements or of the models used to estimate activity data.

For the Tier 1 method, the unit of activity is annual production, preferably measured as the surface area of substrate used during the production of electronic devices. Because annual production may be considered confidential by electronic devices manufacturers, it may be difficult to accurately estimate production at the facility level, and, consequently, at the country level. Further, if annual production is calculated as the product of annual plants' manufacturing capacity and of utilization efficiencies provided by secondary sources (i.e. commercial databases), additional sources of uncertainties can be introduced. This is because manufacturing capacity figures available in commercial databases may be inaccurate, and because capacity utilization figures are often averaged for the global industry or may only be available for certain types of electronic products (e.g. memory, logic, discrete devices). Therefore, inventory compilers should keep in mind that annual production figures calculated from secondary sources may not accurately represent country-specific activities. Because of such limitations, the Tier 1 method should only be used in cases where facility-specific data are not available.

For the Tier 2 and Tier 3 methods, gas consumption constitutes the principal unit of activity to estimate emissions and can therefore be a major potential source of uncertainty and errors. Gas consumption can be either measured or estimated from data on gas purchases, and requires knowledge of the heel, the unused gas returned to gas suppliers in the shipping containers. Using facility-specific heel measurements or accurate heel modelling as opposed to using the default heel value of 0.1 can help reduce uncertainty and error. Another major source of uncertainty and potential errors in activity data is related to gas consumption apportioning, where consumption may need to be distinguished by wafer size (Tier 2b), apportioned to specific process types (Tier 2c), specific recipes or families of similar recipes (Tier 3a), or specific stacks (Tier 3b).

To minimize apportioning uncertainty and increase accuracy, it is *good practice* to implement a gas consumption monitoring system using direct measurement to apportion gas use at the process type-, stack system- or facility-level as appropriate. This can be achieved by various methods including monitoring and integrating the signal of MFCs and using weigh scales; however, it is noted that measurement to specific tools or processes may not be feasible.

Finally, activity data related to the effective use of emissions control systems should be accurately assessed as part of any Tier 2 or Tier 3 method to minimize uncertainties and potential errors. In particular, accurately estimating the fraction of gases used or produced in processes with emissions control technologies (a_i, a_k), the average uptime of emissions control systems (UT), and the overall reduction of input gases and by-products (D_i, D_k) is essential in producing reliable emissions estimates. With respect to the calculation of a_i and a_k in the Tier 2a or Tier 2b estimates, using default gamma values (γ_i and γ_k) to estimate the ratio of the uncontrolled emissions per tool of input gases 'i' or by-products 'k' from thin film deposition tools to the uncontrolled emissions per tool of input gases 'i' or by-products 'k' from etch and wafer cleaning or other tools, introduces a significant source of uncertainty and potential errors (see Table 6.22). Thus, to reduce uncertainty, avoiding the use of gamma default values by apportioning gas consumption by process type (i.e. using the Tier 2c method rather than the Tier 2a or Tier 2b methods) is encouraged.

For fluorinated liquids, the uncertainty of the Tier 2 method will depend on the accuracy of the inventory method. However, accurately tracking the number of fluorinated liquid containers at the beginning and at the end of the year, as well as the total nameplate capacity of equipment that uses fluorinated liquids and that is newly installed in or removed from the fab during the reporting year will ensure that uncertainties are minimized and that fluorinated liquid emissions estimates are reliable.

As described in section 6.3.1, Monte Carlo simulations can be used to estimate the impact of uncertainties in activity data by measuring or modelling the probabilities of distributions functions (PDF) of uncertain activity data, and by combining the PDFs of activity-related variables and the PDFs of emission factors.

TABLE 6.22 (NEW)
TIER 2A & 2B METHODS – ESTIMATES OF RELATIVE UNCERTAINTIES (%) FOR γ_i AND γ_k (SEMICONDUCTOR AND MEMS MANUFACTURING UNDER CERTAIN CONDITIONS*), 95 PERCENT CONFIDENCE INTERVALS

Input gas (γ_i) vs. by-product (γ_k) by wafer size	**Uncertainties by gas and chamber cleaning process type combination**				
	CF_4 (IPC+ITC)/EWC	**C_2F_6 IPC/EWC**	**c-C_4F_8 IPC/EWC**	**NF_3 (IPC+ITC)/EWC**	**SF_6 IPC/EWC**
γ_i (≤200 mm wafer size)	240†	260	200	180†	340
γ_k (≤200 mm wafer size)	220†	340	NA	NA	NA
γ_i (300 mm wafer size)	NA	NA	NA	280†	NA
γ_k (300 mm wafer size)	280†	NA	NA	NA	NA

*Gamma weighting factors for semiconductor manufacturing may be applied to MEMS manufacturing processes that are carried out using semiconductor manufacturing tools when such MEMS processes are similar to semiconductor manufacturing processes (for further details see discussion in the Choice of method section, in particular footnote 3).

† The gamma values for 200 mm were developed based on IPC only and the values for 300 mm were developed based on both ITC and IPC. Gamma is assigned based on analogy due to similar emission factors for IPC and ITC, where known, for the same gas and wafer size.

6.4 QUALITY ASSURANCE / QUALITY CONTROL (QA/QC), REPORTING AND DOCUMENTATION

6.4.1 Quality Assurance / Quality Control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Volume 1, Chapter 6 of the *2019 Refinement*, and an expert review of the emissions estimates. Additional quality control checks as outlined in Volume 1 and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory compilers are encouraged to use higher tier QA/QC for *key categories* as identified in Volume 1, Chapter 4.

Additional general guidance for higher tier QA/QC procedures is also included in Volume 1, Chapter 6 of the *2019 Refinement*. Due to the highly competitive nature of the electronics 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.

It should be noted that comparing Tier 2 and Tier 3a (bottom-up) estimates with Tier 3b (top-down) estimates for representative facilities could help assess the accuracy (or inaccuracy) of the various methods. The Tier 2 and Tier 3a methods are deemed 'bottom-up' approaches because they are based upon consumption at the input of the process tools, while the Tier 3b method is considered a 'top-down' approach as it is based on measuring stack-specific (end of pipe) emission factors. Thus, comparing Tier 2 (or preferably Tier 3a) estimates with Tier 3b estimates would help assess whether biases can exist between top-down and bottom-up estimates.

6.4.2 Reporting and Documentation

Care should be taken not to include emissions of HFCs used as ODS substitutes with those used in electronic devices manufacturing. It is *good practice* to document and archive all information required to produce facility-level and national emissions inventory estimates as outlined in Volume 1, Section 6.11 of the *2019 Refinement*. 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 that steps in their calculation may be retraced.

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 6.23 (Information Necessary for Full Transparency of Estimates of Emissions from Electronics Manufacturing), shows the supporting information necessary for full transparency in reported emissions estimates.

Good practice for Tier 3a and 3b is to document the development of company-specific emission factors, and to explain deviations from default values. Given confidentiality concerns, inventory compilers may wish to aggregate this information across manufacturers. In cases where manufacturers in a country have reported different emission or conversion factors for a given fluorinated compound or N_2O and for specific recipes or families of similar recipes, inventory compilers may provide the range of factors reported and used.

TABLE 6.23 (NEW)
INFORMATION NECESSARY FOR FULL TRANSPARENCY OF ESTIMATES OF EMISSIONS FROM ELECTRONICS MANUFACTURING

Data	Tier 1	Tier 2 (Fluorinated liquids)	Tier 2a	Tier 2b	Tier 2c	Tier 3a	Tier 3b
Annual production, as measured by the surface area of substrate used during the production of electronic devices, including test substrates	X						
Fraction of PV manufacturing capacity that uses FC gases	X						
Inventories of input gases and heat transfer fluids (inventories of containers at the beginning and end of the year, acquisitions, transfers, and (for fluorinated liquids only) nameplate capacity of equipment added or removed during the reporting year		X	X	X	X	X	X
Sizes, types, and total number of different sized containers in the facility			X	X	X	X	X
Types and densities of fluorinated liquids used in the facility		X					
Heel values used for all gases			X	X	X	X	X
Documentation describing the facility-specific apportioning model and demonstration of its accuracy			X	X	X	X	X
Apportioning factors and consumption data for all input gases as a function of wafer size, process types, or stacks as appropriate			X	X	X	X	X
Ratio of process TFD chambers running carbon containing films to total number of TFD chambers			X	X	X	X	

TABLE 6.23 (NEW) (CONTINUED)
INFORMATION NECESSARY FOR FULL TRANSPARENCY OF ESTIMATES OF EMISSIONS FROM ELECTRONICS MANUFACTURING

Data	Tier 1	Tier 2 (Fluorinated liquids)	Tier 2a	Tier 2b	Tier 2c	Tier 3a	Tier 3b
Numbers of EWC and TFD tools equipped with suitable emissions control technologies			X	X	X	X	X
Total numbers of EWC and TFD tools			X	X	X	X	X
Mass fractions of gases and by-products used in processes with emissions control technologies, by process types or stacks as appropriate			X	X	X	X	X
Number and types (manufacturer, model number, technology) of emissions control systems installed in the facility, by process types or stacks			X	X	X	X	X
Documentation describing the facility's procedure to estimate the average uptime of emissions control systems			X	X	X	X	X
Documentation describing the emissions control systems' interlock scheme or the use of back-up emissions control systems (if applicable)			X	X	X	X	X
Average uptime factor of all emissions control systems connected to process tools, by process types or stacks as appropriate			X	X	X	X	X
Overall reduction of input gases and by-products by process types or stacks as appropriate			X	X	X	X	X
Ratio of emissions control systems certified not to form CF_4 within emissions control systems to total number of emissions control systems in the facility			X	X	X	X	
Certifications by original equipment manufacturers (OEMs) that emissions control systems are designed to abate the relevant gases and that the default DREs can be met in the worst-case scenario for the facility			X	X	X	X	X
Documentation showing that emissions control equipment is maintained and operated per manufacturers' specifications			X	X	X	X	X
Measured (facility-specific) destruction removal efficiencies (when default values are not used), and actual measurement reports, including a description of the experimental conditions			X	X	X	X	X

TABLE 6.23 (NEW) (CONTINUED)
INFORMATION NECESSARY FOR FULL TRANSPARENCY OF ESTIMATES OF EMISSIONS FROM ELECTRONICS MANUFACTURING

Data	Tier 1	Tier 2 (Fluorinated liquids)	Tier 2a	Tier 2b	Tier 2c	Tier 3a	Tier 3b
Measured (facility-specific) utilization efficiencies and by-products emission factors, as well as actual measurement reports, including a description of the experimental conditions.						X	X
Flow rates of the stack systems							X

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