

# 1 **CHAPTER 6**

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## 2 **ELECTRONICS INDUSTRY EMISSIONS**

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## 6 ELECTRONICS INDUSTRY EMISSIONS

Users are expected to go to 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*. The substantial refinements of this Chapter include:

- An expanded basket of gaseous fluorinated compounds (FCs) and fluorinated liquids used or produced as by-products during the manufacture of electronic devices, also including the use and emissions of nitrous oxide (N<sub>2</sub>O);
- Revised Tier 1 method with updated emissions factors for the semiconductor, display, microelectromechanical systems (MEMS), and photovoltaic (PV) sub-sectors;
- Guidance on tracking gas consumption and apportioning use to different process types;
- Updated Tier 2 methods with refined approaches to account for emissions control technologies and emissions control technology uptime;
- An update to the Tier 2a method for the semiconductor sub-sector, allowing to estimate emissions over all substrate sizes and process types as a function of input gases;
- An update to the Tier 2b method for the semiconductor sub-sector to account for the size of manufactured wafers and the input gas rather than the process type and input gas;
- A new Tier 2c method for the semiconductor and display sub-sectors that accounts for the size of manufactured wafers (semiconductor) in addition to the process type and input gas;
- A new section on adapting Tier 2 methods to account for technological changes, including guidance on when facility-specific measurements should be considered, and providing guidance for the use of hybrid methodologies (e.g. by combining the Tier 2c and Tier 3a methods);
- An update to the 2006 Tier 3 method (now labelled Tier 3a) to provide guidance on selecting processes for emissions characterizations, including a discussion of “similarity” among recipes;
- A new Tier 3b method that relies on the measurement of emissions at the stack level rather than the process level;
- Updated Tier 1 emission factors for fluorinated liquids;
- Updates to the default emission factors for the Tier 1 and Tier 2 methods, including an expanded list of input gases and by-products; and
- Corresponding updates to the Completeness, Time Series Consistency, Uncertainty, QA/QC, and Reporting and Documentation sections.

Note: Because this chapter completely replaces the corresponding chapter in the *2006 IPCC Guidelines*, the equations, tables, figures, and boxes here have all been renumbered in simple sequential order, without reference to the corresponding equations, tables, figures, or boxes in the *2006 IPCC Guidelines* (where those exist).

### 6.1 INTRODUCTION

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<sub>2</sub>O). The specific electronic industry sub-sectors

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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 devices (OLEDs).

The electronics industry currently emits both FCs that are gases at room temperature and FCs that are liquids at room temperature. 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) 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 occasionally used to clean TFT-display panels during manufacture. Inventory compilers should also account for emissions of nitrous oxide (N<sub>2</sub>O), which is used as an input gas during thin-film deposition (TFD) processes and for “other” N<sub>2</sub>O-using manufacturing processes such as diffusion processes.

For the purpose of this Chapter, FC gases are defined to include perfluoromethane (CF<sub>4</sub>), perfluoroethane C<sub>2</sub>F<sub>6</sub>, perfluoropropane (C<sub>3</sub>F<sub>8</sub>), perfluorocyclobutane (c-C<sub>4</sub>F<sub>8</sub>), 1,3-hexafluorobutadiene (C<sub>4</sub>F<sub>6</sub>), octafluorocyclopentene (c-C<sub>5</sub>F<sub>8</sub>), fluoromethane (CH<sub>3</sub>F), difluoromethane (CH<sub>2</sub>F<sub>2</sub>), trifluoromethane (CHF<sub>3</sub>), pentafluoroethane (C<sub>2</sub>HF<sub>5</sub>), nitrogen trifluoride (NF<sub>3</sub>), sulphur hexafluoride (SF<sub>6</sub>), carbonyl fluoride (COF<sub>2</sub>), fluorine (F<sub>2</sub>), and octafluorotetrahydrofuran (C<sub>4</sub>F<sub>8</sub>O). Further, inventory compilers should consider that fluorinated liquids have appreciable vapour pressures and include perfluoropolyethers, perfluoroalkanes, perfluoroethers, tertiary perfluoroamines, perfluoroalkylmorpholines, and perfluorocyclic ethers. 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 currently believed to include all relevant compounds used in appreciable quantities for the production of electronic devices, 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, emissions of 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 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<sub>2</sub>O-using processes also use plasma or thermal energy to break down N<sub>2</sub>O molecules and generate oxygen or nitrogen atoms or molecules and other excited species to perform the process. The majority of FC gases and N<sub>2</sub>O emissions result from the failure to completely break down the FC gases or N<sub>2</sub>O 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<sub>4</sub>, C<sub>2</sub>F<sub>6</sub>, C<sub>4</sub>F<sub>6</sub>, C<sub>4</sub>F<sub>8</sub>, C<sub>3</sub>F<sub>8</sub>, CHF<sub>3</sub>, CH<sub>2</sub>F<sub>2</sub>, and CH<sub>3</sub>F. Also, formation of CF<sub>4</sub>, C<sub>2</sub>F<sub>6</sub>, CHF<sub>3</sub>, CH<sub>2</sub>F<sub>2</sub>, CH<sub>3</sub>F (and potentially other FC gases) as by-products of etching carbon-containing materials or cleaning chambers previously used to deposit carbon-containing thin films must be taken into account, in particular for processes using molecular fluorine (F<sub>2</sub>, nitrogen trifluoride (NF<sub>3</sub>), sulphur hexafluoride (SF<sub>6</sub>), or chlorine trifluoride (ClF<sub>3</sub>) input gases.<sup>1</sup> It should also be noted that, under certain circumstances, CF<sub>4</sub> may be formed in combustion-based emissions control systems using hydrocarbon fuels by reaction between the fuel and fluorinated species (e.g. F<sub>2</sub>) emitted during F<sub>2</sub> and remote NF<sub>3</sub> chamber cleans, and that an appropriate CF<sub>4</sub> by-product emission factor (AB<sub>i,CF4</sub>) should be used to account for such phenomenon. However, if the emissions control system’s original equipment maker (OEM) or electronics device manufacturer can certify that the mass fraction of NF<sub>3</sub> or F<sub>2</sub> in the process exhaust that is converted into CF<sub>4</sub> is less than 0.1%, inventory compilers may assume that the AB<sub>i,CF4</sub> factor is zero. Finally, with respect to fluorinated liquids, emissions occur through evaporative losses. Please see Section 6.2 on Methodological issues for further details on the proper accounting of emissions from the above-mentioned sources.

The Tier 1 methods 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 subsector (semiconductor, display, MEMS, PV), but the Tier 1 emissions factors (EFs) have been updated to account for technological advancements and for the use of a broader basket of FC gases and fluorinated liquids. As was the case in the *2006 IPCC Guidelines*, the Tier 1 method does not allow accounting for use of emissions control technologies and is the least accurate estimation method. Thus, the Tier 1 methods should be used only in cases where facility-specific data are not available. It should also be noted that, for the MEMS and PV subsectors, insufficient data was available to estimate Tier 2 emission factors and that only the Tier 1 or Tier 3 methodologies can be used for these sub-sectors.

<sup>1</sup> When using cleaning or etching gases that do not contain carbon (e.g. F<sub>2</sub>, NF<sub>3</sub>, SF<sub>6</sub>, or ClF<sub>3</sub>), CF<sub>4</sub> 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<sub>4</sub> 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<sub>2</sub>, COF<sub>2</sub>, or ClF<sub>3</sub>). Please see section 6.2.2.1 for more detail.

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, the high Tier 1 for SF<sub>6</sub> emission factor corresponds to a MEMS specific process consisting of etching vias through the substrate, a process which consumes significant amounts of SF<sub>6</sub>. Thus, inventory compilers are encouraged to use the Tier 3a or Tier 3b method for MEMS if evidence indicates that actual emissions may diverge from the MEMS Tier 1 defaults; moreover, manufacturing processes for certain types of MEMS may be similar to semiconductor processes, in which case, semiconductor Tier 1 or Tier 2 default emissions factors may be more appropriate.

The 2006 Tier 2a method is updated as a new refined 2019 Tier 2a method for the 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 display manufacturers have historically used the 2006 Tier 2b method; moreover, there is no need for a Tier 2a method for the display sub-sector because the display industry has separate gas supplies for each process type and process-type specific emission factors can be used. For the display sub-sector, the 2006 Tier 2b method is now replaced by the new Tier 2c method.

The 2006 Tier 2b method, which used to distinguish emission factors by process types (etch versus chemical vapor deposition (CVD)) is now replaced with a new refined 2019 Tier 2b method using emission factors applicable to different wafer sizes for the semiconductor sub-sector ( $\leq 200$  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 not applicable to the display sub-sector (only to the semiconductor sub-sector).

The new 2019 Tier 2c method for the semiconductor sub-sector allows to distinguish emissions factors by both wafer size ( $\leq 200$  mm or 300 mm), and by refined process types. For the semiconductor sub-sector there are now 6 refined process types: 1) etch or wafer cleaning (EWC), 2) remote plasma cleaning (RPC), 3) in-situ plasma cleaning (IPC), 4) in-situ thermal cleaning (ITC), 5) thin film deposition (TFD) processes using N<sub>2</sub>O, 6) and 'Other' N<sub>2</sub>O processes (i.e. N<sub>2</sub>O-using processes that are not TFD processes, such as N<sub>2</sub>O-using diffusion processes). For the display sub-sector, the Tier 2c method does not distinguish by substrate size but provides differentiated emission factors by process types. However, for the display sub-sector, there are only 4 distinct process types defined as 1) etching, 2) remote plasma cleaning (RPC), 3) in-situ plasma cleaning (IPC), and 4) thin film deposition (TFD).

Using the Tier 2 methods requires some degree of apportioning of gas consumption. That is, the consumption of input gases must be differentiated by process type (e.g. etching vs. chamber cleaning). It should be noted that the extent of apportioning is limited for the Tier 2a and 2b methods (where differentiation is only required between the RPC and other NF<sub>3</sub>- or C<sub>3</sub>F<sub>8</sub>-using processes), but that the Tier 2c method requires apportioning over a larger number of process types, increasing the complexity of the Tier 2c method but providing refined estimates compared to the lowered tiered methods. 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. 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.

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*.



## 6.2 METHODOLOGICAL ISSUES

### 6.2.1 Choice of Method

#### 6.2.1.1 ETCHING AND TFD CLEANING FOR SEMICONDUCTORS, LIQUID CRYSTAL DISPLAYS, AND PHOTOVOLTAICS

GHG emissions from the electronics industry vary according to the gases and process types used in manufacturing, as well as the type, and the implementation of emissions control technologies. The choice of methods will depend on data availability and is outlined in the decision tree of Figure 6.1 (Decision tree for estimation of GHG emissions from electronics manufacturing) and in Table 6.1 (Information for sources necessary for completing the tiered emissions estimating methods for electronics manufacturing).

Continuous (in-situ) emissions monitoring is not currently considered an economically viable means to estimate emissions from the electronics industry. Greenhouse gas emissions are periodically measured at the process tool exhaust during the development of new processes and tools, generally for centreline process conditions.<sup>2</sup> In addition, 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. While the Tier 1 and Tier 2a, 2b, and 2c methods are based on averaged (default) emission factors based on a large set of measured processes from a host of sources across industry, the higher tiered methods are based on measured emission factors for specific process recipes or families of similar process recipes (Tier 3a), or site-specific emission factors derived from stack measurements (Tier 3b).

It is very important to note that emission factors for input gas utilisation efficiencies and by-product formation rates can be strongly affected by changes in process variables (e.g. substrate size, process type/subtype, film removed in TFD chamber cleans, tool platform, combination of gases used, etc.), and that 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. Further, emission factors are affected by the design of the process reactors and will 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.). In addition, the efficacy of greenhouse gas emissions control equipment depends on whether it is designed to abate the target gas and on operating and maintaining the equipment according to the manufacturer’s specifications, especially as regards to not exceeding individual process gas and total gas flow rates (including any added purge gases) as stated by the emissions control equipment supplier. As presented in Figure 6.1 and Table 6.1, the choice of a particular method will depend on the availability of information regarding substrate production capacity, the consumption of input gases, and the processes utilising input gases. The uncertainty of estimated emissions depends on the method used. Generally, higher tiered methods are expected to be more accurate than the lower tiers and using site-specific emission factors will reduce the uncertainty and increase the accuracy of emissions estimates. The accuracy of the methods using default emission factors (Tier 1, Tier 2a, 2b, 2c) essentially depends, among other things, on the differences between the emission factors of the processes actually used in production and the averaged (default) emission factors of a particular method, as well as on potential errors in apportioning gas consumption, and in reporting emissions control equipment efficiency and uptime. With respect to uncertainty, the confidence level of a particular estimate is principally driven by the uncertainty of the default emission factors, which frequently show relative errors of greater than 100% (see Section 6.3.1) and of gas consumption tracking and apportioning (see Section 6.3.2). 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, emissions can be estimated using the Tier 1 method based on production figures (surface area of substrate used during the production of electronic devices), but this approach is the least accurate and should be used only in cases where company-specific gas consumption data is not available. Further, the Tier 1 method does not allow to account for the use of emissions control technology. Note that insufficient data was available to calculate Tier 2 factors for PV and MEMS manufacturing; hence, only the Tier 1 method or the Tier 3a or 3b methods are available to estimate emissions from these sub-sectors. As noted earlier, if MEMS are manufactured in semiconductor facilities, semiconductor Tier 2 methods and defaults may be more appropriate. The choice of method will also depend on whether companies track gas

<sup>2</sup> 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.

usage by substrate size and/or by process type which are the key criteria for selecting between the Tier 2a, 2b, and 2c methods.

For the semiconductor sub-sector, the key distinction between the Tier 2a and Tier 2b methods is that the Tier 2b method provides emissions factors that depend on wafer size ( $\leq 200$  mm or 300 mm). The Tier 2a method does not distinguish between substrate size and 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. It should also be noted that the Tier 2a and 2b methods do not generally allow for distinguishing emission factors by process type; however, a limited amount of apportionment of  $\text{NF}_3$  and  $\text{C}_3\text{F}_8$  consumption is still required because emission factors are significantly different for the remote clean technology and for other ( $\text{NF}_3$ - or  $\text{C}_3\text{F}_8$ -using) processes. Moreover, the  $\text{N}_2\text{O}$  emission factors are different for  $\text{N}_2\text{O}$  TFD processes and for 'other'  $\text{N}_2\text{O}$ -using processes (for all other gases there are no distinctions in the Tier 2a and Tier 2b methods between process types). Because emission factors are generally dependent on process type, the Tier 2a and 2b methods should only be used when it is not possible to distinguish (apportion) gas consumption between process types, or in cases where the gas consumption apportionment model proves to introduce greater uncertainty than using the more accurate process-type-dependent Tier 2c emission factors.

The Tier 2c method is the preferred Tier 2 sub-method and is believed to provide more accurate emission estimates than other Tier 1 or Tier 2 methods because the Tier 2c default emission factors distinguish between both substrate size in the semiconductor sub-sector and process type. The Tier 2c method is the only Tier 2 method available for the display sub-sector. In the case of the Tier 2c method for the semiconductor sub-sector, process-types are 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)  $\text{N}_2\text{O}$  TFD, and 6)  $\text{N}_2\text{O}$  'other'. In the case of the Tier 2c method for the display sub-sector, process types are defined as 1) etching, 2) remote plasma cleaning (RPC), 3) in-situ plasma cleaning (IPC), and 4)  $\text{N}_2\text{O}$  TFD. It should be noted that distinguishing emission factors by process type require apportionment of gas consumption to each process type; for example, if  $\text{NF}_3$  is used for both remote plasma cleaning, in-situ plasma cleaning, and etching, then the amount of  $\text{NF}_3$  consumed for each of these three process types must be apportioned.

**BOX 6.1 (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 must be taken into account. To this effect, by-product emission factors ( $B_{\text{CF}_4,i}$ ,  $B_{\text{C}_2\text{F}_6,i}$ ,  $B_{\text{C}_3\text{F}_8,i}$ ,  $B_{\text{C}_4\text{F}_6,i}$ ,  $B_{\text{C}_4\text{F}_8,i}$ ,  $B_{\text{C}_5\text{F}_8,i}$ ,  $B_{\text{CH}_3\text{F}_i}$ ,  $B_{\text{CH}_2\text{F}_2,i}$ , and  $B_{\text{CHF}_3,i}$ , 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.  $\text{NF}_3$ ,  $\text{SF}_6$ ,  $\text{F}_2$ ). This is because the fluorine atoms and other excited F species generated from the decomposition of  $\text{NF}_3$ ,  $\text{SF}_6$  or  $\text{F}_2$  can react with the carbon contained in the film to form  $\text{CF}_4$  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  $\text{NF}_3$ ,  $\text{SF}_6$ ,  $\text{F}_2$  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  $\text{CF}_4$  or other carbon-containing greenhouse gases are expected to be formed during the process.

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, but –instead of using default emission factors and being limited to six process types (semiconductor sub-sector) or four process types (display sub-sector)– uses, at least in part, measured facility-specific emission factors. In theory, the Tier 3a method could be used to assign an emission factor to each centreline process, or to assign a specific destruction removal efficiency 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, and that using the refined Tier 3a method does not require using 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). While the Tier 3a method is based on a 'bottom-up' approach, where reporting companies measure and add up emissions from individual process runs, the Tier 3b method is based on a 'top-

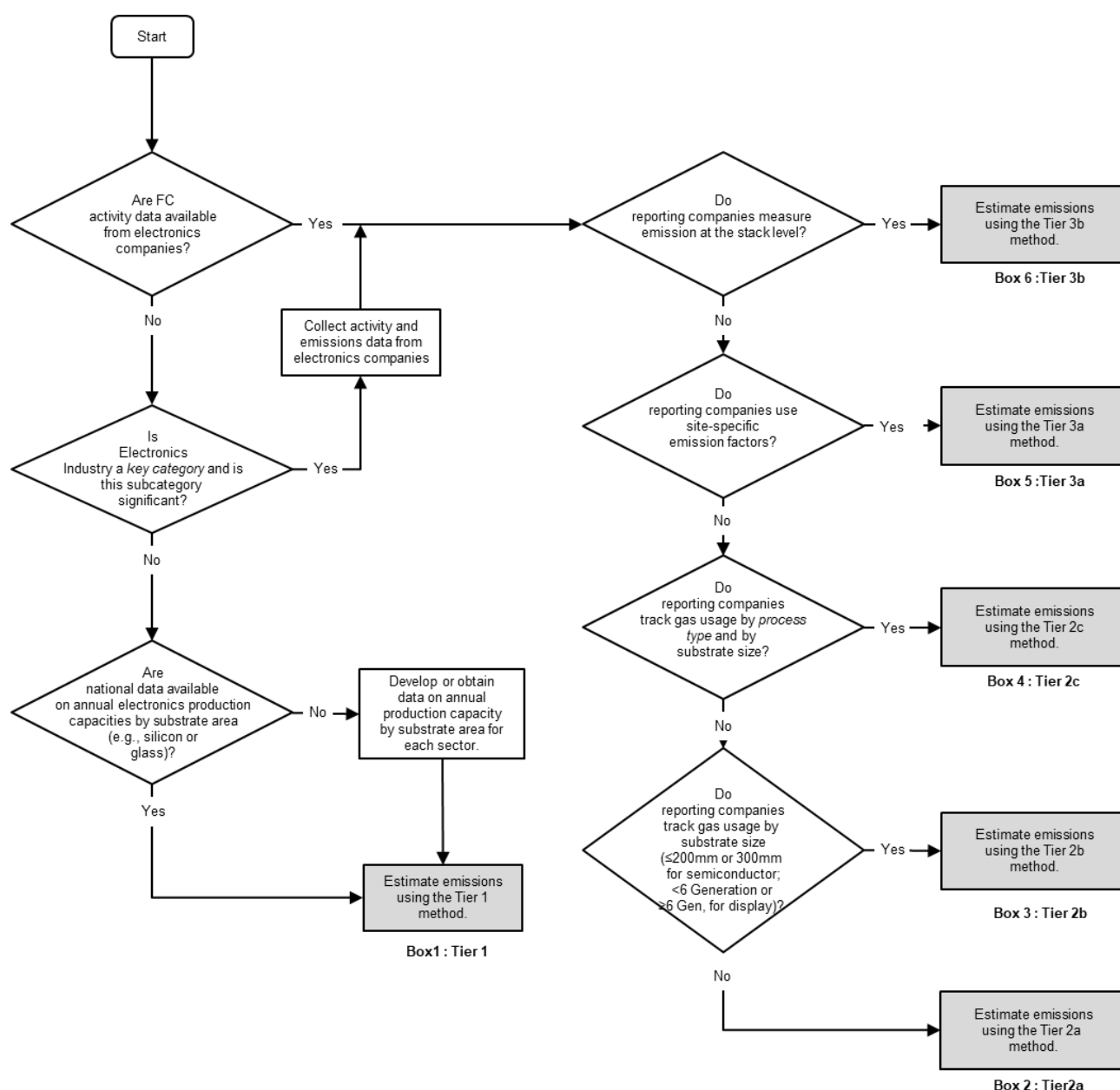
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down' approach, where reporting companies measure emissions at the stack (end of pipe) level. In the case of the Tier 3b method, reporting companies estimate their emissions based on fab-specific emission factors. These emission factors are developed through periodic measurements of stack emissions correlated to 1) the consumption of input gases by the production tools connected to the stack, and 2) the efficacy of the emissions control technologies used with those tools.

With respect to accounting for emissions control technologies, it should be noted that the *2019 Refinement* includes a significant elaboration, which is the consideration of the uptime of emissions control systems. Also, guidance is provided 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. 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., a new process type/subtype is introduced), facilities can undertake process emissions characterization under Tier 3a and measure (1-U) and BPE factors for those new processes without defaults 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****Notes:**

Even though the logic depicted in Figure 6.1 does not show the possibility of combining tiers, facilities can undertake process emissions characterization under Tier 3a and measure (1-U) and BPE factors for some site-specific processes (recipes or families of 'similar' recipes) while using Tier 2 defaults for processes for which no site-specific emission factors are available. Similarly, facilities could undertake the Tier 3b method for some of the stacks in the facility and use a Tier 3a or Tier 2 methods for other parts of the facility. See section "ADAPTING TIER 2 METHODS TO ACCOUNT FOR TECHNOLOGICAL CHANGES" for more details.

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.

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Table 6.1 presents 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 6.1 (UPDATED)						
INFORMATION SOURCES NECESSARY FOR COMPLETING THE TIERED EMISSIONS ESTIMATING METHODS FOR ELECTRONICS MANUFACTURING						
<b>Note:</b> variables are listed in their order of appearance in the equations of the 2019 <i>Refinement</i> . Variables common to multiple equations are presented the first time they appear in an equation and are not replicated, unless equation-specific variations apply. <b>Legend:</b> Me = measured; Mo = modelled; D = default factors from guidance; C = calculated.						
Variables	Tier 1	Tier 2			Tier 3	
		2a	2b	2c	3a	3b
$\{E_i\}_n$ = emissions of fluorinated compound gas $i$ ( $FC_i$ ) or $N_2O$ (kg)	C					
$EF_i$ = 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 $i/m^2$ )	D					
$P$ = 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)	Me/Mo					
$F_{PV}$ = fraction of PV manufacture that uses FC gases, fraction	Me/Mo					
$\delta = 1$ when applied to PV industry and zero when applied to either semiconductor or TFT-Display industries, dimensionless.	D					
$C_i$ = Annual consumption of gas $i$ (site specific, kg per year)		C	C	C	C	C
$IB_i$ = Inventory of input gas $i$ stored in containers at the beginning of the reporting year, including heels (site-specific, kg).		Me	Me	Me	Me	Me
$IE_i$ = Inventory of input gas $i$ stored in containers at the end of the reporting year, including heels (site-specific, kg).		Me	Me	Me	Me	Me
$A_i$ = Acquisitions of input gas $i$ during the year through purchases or other transactions, including heels in containers returned to the electronics manufacturing facility (site-specific, kg)		Me	Me	Me	Me	Me
$T_i$ = 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 (site-specific, kg)		C	C	C	C	C
$h_{i,l}$ = Gas-specific heel factor for input gas $i$ and container size and type $l$ (fraction).		D/Me	D/Me	D/Me	D/Me	D/Me
$N_{i,l}$ = Number of containers of size and type $l$ used at the reporting facility and returned to the gas distributor containing the standard heel of input gas $i$		Me	Me	Me	Me	Me
$F_{i,l}$ = Full capacity of containers of size and type $l$ containing input gas $i$ (kg)		Me	Me	Me	Me	Me
$M$ = Total number of different sized container types for the reporting facility. If only one size and container type is used for an input gas $i$ , $M = 1$ .		Me	Me	Me	Me	Me
$C_{i,p}$ = Annual amount of input gas $i$ consumed by the reporting facility for process type $p$ (kg)		C	C	C	C	
$\Phi_{i,p}$ = Process type $p$ -specific apportioning factor for input gas $i$ (fraction)		Me/Mo	Me/Mo	Me/Mo	Me/Mo	
$E_i$ = Emissions of unreacted input gas $i$ (kg)		C	C	C	C	
$U_i$ = Use rate of gas $i$ (fraction destroyed or transformed in process) (fraction)		D	D			
$D_i$ = Overall reduction of gas $i$ emissions (site-specific fraction)		C	C			
$BPE_k$ = Emissions of by-product $k$ generated from the conversion of all input gases $i$ (kg)		C	C			
$B_{k,i}$ = Emission factor for by-product $k$ generated from input gas $i$ (kg of by-product $k$ created per kg of gas $i$ consumed, fraction)		D	D			
$D_k$ = Overall reduction of gas $k$ by-product emissions (site-specific fraction)		C	C			

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<b>TABLE 6.1 (UPDATED) (CONTINUED)</b> <b>INFORMATION SOURCES NECESSARY FOR COMPLETING THE TIERED EMISSIONS ESTIMATING METHODS FOR ELECTRONICS MANUFACTURING</b>						
<b>Note:</b> variables are listed in their order of appearance in the equations of the 2019 <i>Refinement</i> . Variables common to multiple equations are presented the first time they appear in an equation and are not replicated, unless equation-specific variations apply. <b>Legend:</b> Me = measured; Mo = modelled; D = default factors from guidance; C = calculated.						
Variables	Tier 1	Tier 2			Tier 3	
		2a	2b	2c	3a	3b
EAB <sub>i,CF4</sub> = Emissions of CF <sub>4</sub> from hydrocarbon-fuel-based combustion emissions control systems when direct reaction with hydrocarbon fuel and fluorinated species is not certified by the emissions control equipment OEM or electronics manufacturer		C	C	C	C	
$\eta$ = Ratio of emissions control systems certified not to form CF <sub>4</sub> within emissions control systems to the total number of emissions control systems in the facility (site-specific fraction)		Me	Me			
AB <sub>i,CF4</sub> = Mass fraction of NF <sub>3</sub> or F <sub>2</sub> in process exhaust gas that is converted into CF <sub>4</sub> by direct reaction with hydrocarbon fuel and F <sub>2</sub> gas in a combustion emissions control system.		D	D	D	D	
a <sub>i</sub> = Estimate of the fraction of gas i emitted from process tools equipped with suitable emissions control technologies (site-specific fraction)		C	C			
d <sub>i</sub> = Destruction Removal Efficiency (DRE) for gas i (fraction)		D	D	D	D/Me	D/Me
UT = Average uptime factor of all emissions control equipment systems (site-specific fraction)		C	C			
a <sub>k</sub> = Estimate of the fraction of by-product k emitted from process tools equipped with suitable emissions control technologies (site-specific fraction)		C	C			
d <sub>k</sub> = Destruction Removal Efficiency (DRE) for by-product k (fraction)		D	D	D	D/Me	D/Me
na <sub>i</sub> = Number of tools using gas i, running process type 1, and that are equipped with suitable emissions control technologies for gas i (site-specific)		Me	Me			
ma <sub>i</sub> = Number of tools using gas i, running process type 2, and that are equipped with suitable emissions control technologies for gas i (site-specific)		Me	Me			
n <sub>i</sub> = Total number of tools using gas i and running process type 1 (site-specific)		Me	Me			
m <sub>i</sub> = Total number of tools using gas i and running process type 2 (site-specific)		Me	Me			
$\gamma_i$ = Default factor reflecting the ratio of uncontrolled emissions of input gas i from tools running process type 1 to uncontrolled emissions of input gas i from process tools running process type 2 (fraction)		D	D			
na <sub>k</sub> = Number of tools emitting by-product k, running process type 1, and that are equipped with suitable emissions control technologies for by-product k (site-specific)		Me	Me			
ma <sub>k</sub> = Number of tools emitting by-product k, running process type 2, and that are equipped with suitable emissions control technologies for by-product k (site-specific)		Me	Me			
n <sub>k</sub> = Total number of tools producing by-product k and running process type 1 (site-specific)		Me	Me			
m <sub>k</sub> = Total number of tools producing by-product k and running process type 2 (site-specific)		Me	Me			
$\gamma_k$ = Default factor reflecting the ratio of uncontrolled emissions of by-product k from process tools running process type 1 to uncontrolled emissions of by-product k from process tools running process type 2 (fraction)		D	D			

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<b>TABLE 6.1 (UPDATED) (CONTINUED)</b> <b>INFORMATION SOURCES NECESSARY FOR COMPLETING THE TIERED EMISSIONS ESTIMATING METHODS FOR ELECTRONICS MANUFACTURING</b>						
<b>Note:</b> variables are listed in their order of appearance in the equations of the 2019 Refinement. Variables common to multiple equations are presented the first time they appear in an equation and are not replicated, unless equation-specific variations apply. <b>Legend:</b> Me = measured; Mo = modelled; D = default factors from guidance; C = calculated.						
Variables	Tier 1	Tier 2			Tier 3	
		2a	2b	2c	3a	3b
$Td_n$ = 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)		Me	Me			
$TT_n$ = Total time during which emissions control system n has at least one associated manufacturing tool in operation (minutes per year)		Me	Me			
$U_{i,p}$ = Use rate of gas i for process p (fraction destroyed or transformed in process p)				D	Me	
$D_{i,p}$ = Overall reduction of mass of gas i emitted from process type p (site-specific fraction)				C	C	
$BPE_k$ = Emissions of by-product k generated from the conversion of all input gases i for all process types p (kg)				C	C	
$B_{k,i,p}$ = 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)				D	Me	
$D_{k,p}$ = Overall reduction of mas of gas k by-product emissions for process type p (site-specific fraction)				C	C	
$\eta_p$ = Ratio of emissions control systems connected to tools running process type p and certified not to form CF <sub>4</sub> within emissions control systems to the total number of emissions control systems running process type p in the facility (site-specific fraction)				Me	Me	
$a_{i,p}$ = 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)				C	C	
$UT_p$ = Average uptime factor of all emissions control systems connected to tools running process type p (site-specific fraction)				C	C	
$a_{k,p}$ = 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)				C	C	
$na_{i,p}$ = Number of process tools running process type p (emitting gas i) that are equipped with suitable emissions control technologies (site-specific)				Me	Me	
$n_{i,p}$ = Total number of process tools running process type p and emitting gas i (site-specific)				Me	Me	
$ma_{k,p}$ = Number of process tools running process type p (emitting by-product k) that are equipped with suitable emissions control technologies (site-specific)				Me	Me	
$m_{k,p}$ = Total number of process tools running process type p and emitting by-product k (site-specific)				Me	Me	
$Td_{n,p}$ = 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)				Me	Me	
$TT_{n,p}$ = Total time during which emissions control system n has at least one associated manufacturing tool running process type p in operation (minutes per year)				Me	Me	
$E_{i,s}$ = Annual emissions of input gas i from stack system s (kg CO <sub>2</sub> e)						C
$C_{i,s}$ = Amount of input gas i consumed for stack system s (kg).						Me/Mo

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<b>TABLE 6.1 (UPDATED) (CONTINUED)</b> <b>INFORMATION SOURCES NECESSARY FOR COMPLETING THE TIERED EMISSIONS ESTIMATING METHODS FOR ELECTRONICS MANUFACTURING</b>						
<b>Note:</b> variables are listed in their order of appearance in the equations of the 2019 <i>Refinement</i> . Variables common to multiple equations are presented the first time they appear in an equation and are not replicated, unless equation-specific variations apply. <b>Legend:</b> Me = measured; Mo = modelled; D = default factors from guidance; C = calculated.						
Variables	Tier 1	Tier 2			Tier 3	
		2a	2b	2c	3a	3b
$a_{i,s}$ = Estimate of the fraction of gas $i$ emitted from process tools connected to stack system $s$ and equipped with suitable emissions control technologies used in processes with emissions control technologies (site-specific fraction)						C
$UT_s$ = Average uptime factor of all emissions control systems connected to process tools connected to stack system $s$ (site-specific fraction)						C
$GWP_i$ = Global Warming Potential of gas $i$ (kg CO <sub>2</sub> e/ kg gas $i$ )						D
$Td_{n,s}$ = Total time that emissions control equipment system $n$ connected to process tools associated with stack system $s$ in the facility is not in operational mode when at least one of the manufacturing tools connected to emissions control equipment system $n$ is in operation (minutes per year)				Me	Me	
$TT_{n,s}$ = Total time during which emissions control equipment system $n$ has at least one associated manufacturing tool associated with stack $s$ in operation (minutes per year)				Me	Me	
$GWP_k$ = Global Warming Potential of by-product $k$ (kg CO <sub>2</sub> e/ kg by-product $k$ )						D
$ES_{i,s}$ = Emissions of input gas $i$ from stack system $s$ during the sampling period (kg)						C
$MW_i$ = Molecular weight of gas $i$ (g/g-mole)						D
$Q_s$ = Flow rate of stack system $s$ during the sampling period (m <sup>3</sup> /min)						Me
$SV$ = Standard molar volume of gas						D
$X_{i,s,m}$ = Average concentration of input gas $i$ in stack system $s$ during time interval $m$ (ppbv)						Me
$\Delta t_m$ = Length of time interval $m$ in the FTIR sampling period (minutes)						Me
$N$ = Total number of time intervals $m$ in sampling period						Me
$ES_{k,s}$ = Emissions of by-product $k$ emitted from stack system $s$ during the sampling period (kg)						C
$MW_k$ = Molecular weight of by-product gas $k$ (g/g-mole)						D
$X_{k,s,m}$ = Average concentration of by-product $k$ in stack system $s$ during time interval $m$ (ppbv)						Me
$EF_{i,f}$ = Emission factor for input gas $i$ and facility $f$ representing 100 percent emissions control system uptime (kg emitted per kg of input gas consumed)						C
$\theta$ = Fraction of total fab emissions included in the tested stacks based on preliminary estimates (site-specific fraction).						C
$Activity_{i,f}$ = Consumption of input gas $i$ for facility $f$ during the stack testing period (kg)						Me
$UT_f$ = Total uptime factor of all emissions control systems for facility $f$ during the sampling period (site-specific fraction) or during the reporting year.						Me
$a_{i,f}$ = Estimate of the fraction of gas $i$ emitted from process tools equipped with suitable emissions control technologies for facility $f$ (site-specific fraction)						C
$EF_{k,f}$ = Emission factor for by-product gas $k$ emitted from facility $f$ , representing 100 percent emissions control system uptime (kg emitted per kg of all input gases $i$ consumed)						C
$a_{k,f}$ = Estimate of the fraction of by-product emitted from process tools equipped with suitable emissions control technologies for facility $f$ (site-specific fraction)						C
$EA_{i,f}$ = Annual emissions of input gas $i$ from the stack systems that are tested for facility $f$ (kg/year)						C

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<b>TABLE 6.1 (UPDATED) (CONTINUED)</b> <b>INFORMATION SOURCES NECESSARY FOR COMPLETING THE TIERED EMISSIONS ESTIMATING METHODS FOR ELECTRONICS MANUFACTURING</b>						
<b>Note:</b> variables are listed in their order of appearance in the equations of the 2019 Refinement. Variables common to multiple equations are presented the first time they appear in an equation and are not replicated, unless equation-specific variations apply. <b>Legend:</b> Me = measured; Mo = modelled; D = default factors from guidance; C = calculated.						
Variables	Tier 1	Tier 2			Tier 3	
		2a	2b	2c	3a	3b
$C_{i,f}$ = Total consumption of input gas $i$ for facility $f$ for the reporting year (kg/year)						Me
$EA_{k,f}$ = Annual emissions of by-product $k$ from the stack systems that are tested for facility $f$ (kg/year)						C
$Td_{n,f}$ = The total time, in minutes, that emissions control system $n$ , connected to process tool(s) in fab $f$ , is not in operational mode						Me
$TT_{n,f}$ = Total time, in minutes per year or in minutes of sampling time in which the tool(s) connected at any point during the year to emissions control system $n$ , in fab $f$ could be in operation.						Me
$FC_i$ = Emissions of fluorinated liquid $i$ (kg)	C	C	C	C	C	C
$\rho_i$ = Density of fluorinated liquid $i$ (kg/litre)		Me	Me	Me	Me	Me
$I_{i,t-1}$ = Inventory of liquid $FC_i$ in containers other than equipment at the beginning of the reporting year (litres in stock or storage)		Me	Me	Me	Me	Me
$P_{i,t}$ = Acquisitions of fluorinated 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)		Me	Me	Me	Me	Me
$N_{i,t}$ = 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)		Me	Me	Me	Me	Me
$R_{i,t}$ = 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)		Me	Me	Me	Me	Me
$I_{i,t}$ = Inventory of fluorinated liquid $FC_i$ in containers other than equipment at the end of the reporting year (litres in stock or storage)		Me	Me	Me	Me	Me
$D_{i,t}$ = 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)		Me	Me	Me	Me	Me

## 443 TIER 1 METHOD – DEFAULT

444 The Tier 1 method is the least accurate estimation method and should be used only in cases where facility-specific  
 445 data are not available. The Tier 1 method is based on production figures (surface area of substrate used during the  
 446 production of electronic devices, e.g. silicon, glass). Unlike the Tier 2 or Tier 3 methods, the Tier 1 method is  
 447 designed to give an aggregated estimate of greenhouse gas and N<sub>2</sub>O emissions with an estimated but uncertain  
 448 break-out among specific gases. Estimates are made simultaneously for all the gases listed in Table 6.2, and the  
 449 Tier 1 method can only be used if these gases are reported as a complete set. For each class (sub-sector) of  
 450 electronic products being manufactured (semiconductors, display, PV, MEMS), the calculation of emissions relies  
 451 on a different set of default, gas-specific emission factors. Each default emission factor expresses the average  
 452 emissions of the relevant gas per unit area of the relevant substrate used during manufacture (including test  
 453 substrates).

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

$$\text{EQUATION 6.1 (UPDATED)}$$

$$\text{TIER 1 METHOD FOR ESTIMATION OF THE SET OF GHG EMISSIONS}$$

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

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 6.2). 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 6.2.

$P$  = 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

$\delta = 1$  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 differences 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 6.2. 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

In using Tier 2 and Tier 3 methods, input gas consumption ( $C_i$ ) must be determined and apportioned to specific process types ( $C_{i,p}$ ). 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.

$$\text{EQUATION 6.2 (NEW)}$$

$$\text{CONSUMPTION OF INPUT GAS I}$$

$$C_i = (IB_i - IE_i + A_i - T_i)$$

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 (site-specific, 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 (site-specific, 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 (site-specific, 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 (site-specific, kg).

$i$  = Input gas.

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509 Transfers ( $T_i$ ) are calculated using Equation 6.3.

**EQUATION 6.3 (NEW)**  
**TRANSFERS OF INPUT GAS I**

$$T_i = \sum_{l=1}^M h_{i,l} \cdot N_{i,l} \cdot F_{i,l}$$

510 Where:

511  $T_i$  = Transfers of input gas  $i$  through sales or other transactions during the reporting year for the reporting  
512 facility, including heels in containers returned by the electronics manufacturing fab to the gas  
513 distributor (kg).

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

516  $N_{i,l}$  = Number of containers of size and type  $l$  used at the reporting facility and returned to the gas distributor  
517 containing the standard heel of input gas  $i$ .

518  $F_{i,l}$  = Full capacity of containers of size and type  $l$  containing input gas  $i$  (kg).

519  $i$  = Input gas.

520  $l$  = Size and type of gas container.

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

523 A site-specific heel factor for each type of gas and container used in a facility ( $h_{i,l}$ ) can be determined by monitoring  
524 the pressure and converting the pressure to mass using the ideal gas law or based on the weight of the gas provided  
525 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  
526 reporting year, inventory compilers may assume that any  $h_{i,l}$  for that FC gas or  $N_2O$  is equal to zero.

527 For the Tier 2 and Tier 3 methods, varying degrees of gas use apportioning are required. For the semiconductor  
528 sub-sector, the Tier 2a and 2b methods require apportioning of  $NF_3$  and  $C_3F_8$  consumption between the Remote  
529 Plasma Clean process type and other  $NF_3$ - or  $C_3F_8$ -using process types, while  $N_2O$  is apportioned between the  $N_2O$   
530 TFD process type and "Other"  $N_2O$ -using process types. For the semiconductor and display sub-sectors, the Tier  
531 2c method requires apportioning for each input gas  $i$  and each process type  $p$ . Apportioning is calculated using  
532 Equation 6.4.

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

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

536 Where:

537  $C_{i,p}$  = Annual amount of input gas  $i$  consumed by the reporting facility for process type  $p$  (kg).

538  $\Phi_{i,p}$  = Process type  $p$ -specific apportioning factor for input gas  $i$  (fraction).

539  $C_i$  = Annual consumption of input gas  $i$  for the reporting facility, as calculated using Equation 6.2 (kg).

540  $i$  = input gas.

541 To minimize apportioning uncertainty and increase accuracy, it is *good practice* where feasible to implement a gas  
542 consumption monitoring system using direct measurement to apportion gas use at the process type-, stack system-  
543 or facility-level as appropriate. This can be achieved by various methods including monitoring and integrating the  
544 signal of Mass Flow Controllers (MFCs) and using weigh scales. However, if gas consumption measurement at  
545 the process level is not deemed feasible for a particular facility, apportioning factors ( $\Phi_{i,p}$ ) can be calculated using  
546 a site-specific engineering model. This model should be based on a quantifiable metric, such as substrate passes  
547 or substrate starts. To verify the apportioning model, inventory compilers should demonstrate its precision and  
548 accuracy by adhering to the following requirements:

- 549 (1) Inventory compilers should demonstrate that the FC gases and  $N_2O$  apportioning factors are developed using  
550 calculations that are repeatable, which means that the variables used in the formulas for the facility's  
551 engineering model for gas apportioning factors should be based on observable and measurable quantities that  
552 govern gas consumption rather than engineering judgment about those quantities or gas consumption. Note  
553 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 must be included in emissions calculation. In the event of the introduction of new manufacturing technologies or new gases, this demonstration should be repeated.

(2) Inventory compilers should 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 period when the fab is at a representative operating level for a period lasting at least 30 days but no more than the reporting year. Representative operating levels means operating the fab, in terms of substrate starts for the period of testing or monitoring, at no less than 50 percent of installed production capacity or no less than 70 percent of the average production rate for the reporting year, where the production rate for the reporting year is represented in average monthly substrate starts. For the purposes of stack testing, the period for determining the representative operating level should be the period ending on the same date on which testing is concluded. In the event of the introduction of new technologies and/or significant changes to wafer throughput or wafer diameter, this analysis should be repeated.

(ii) Comparing the actual gas consumed to the modelled gas consumed for the highest use fluorinated compound which is used in multiple process types reported for the facility (e.g., NF<sub>3</sub> use in remote clean and other processes). Inventory compilers may compare the actual gas consumed to the modelled gas consumed for two fluorinated compounds and demonstrate conformance on an aggregate use basis for both fluorinated compounds if one of the fluorinated compounds selected for comparison corresponds to the largest quantity, on a mass basis, of fluorinated compounds used at each facility that requires apportionment during the reporting year.

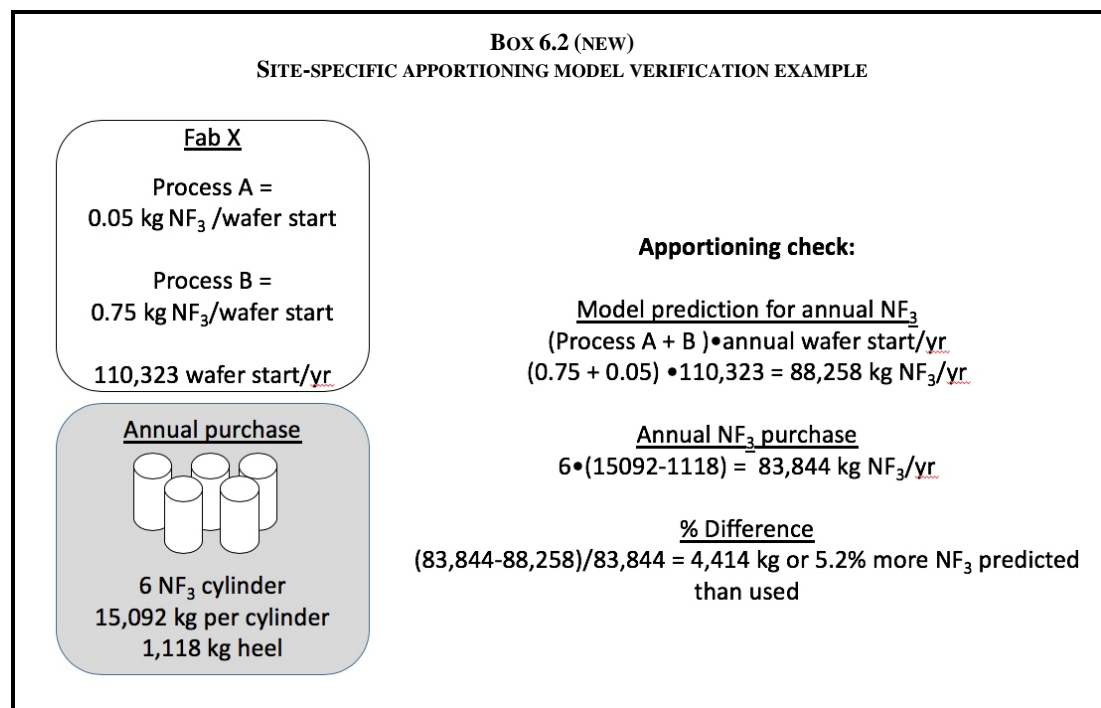
(iii) Demonstrating that the comparison performed for the largest quantity of gas(es), on a mass basis, consumed in the facility, does not result in a difference between the actual and modelled gas consumption that exceeds 20 percent relative to actual gas consumption, reported to two significant figures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

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

3) As an alternative to developing apportioning factors for fluorinated compounds and N<sub>2</sub>O consumption using a site-specific engineering model, inventory compilers may develop apportioning factors through the use of direct measurement using gas flow meters and weigh scales to measure process type, stack system, or fab-specific input gas consumption. 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. Note that it is considered *good practice* to use direct measurement of gas consumption because such practice can significantly reduce uncertainty through accurate apportioning; however, it is noted that measurement to specific tools or processes may not be feasible.

Box 6.2 provides an example of a site-specific apportioning model verification.

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While the Tier 2c method requires apportioning for each input gas  $i$  and each process type  $p$ , the Tier 2a and 2b methods only require minimal apportioning to distinguish NF<sub>3</sub> and C<sub>3</sub>F<sub>8</sub> consumption between the Remote Plasma Clean process type and other NF<sub>3</sub>- or C<sub>3</sub>F<sub>8</sub>-using process types, as well as between the N<sub>2</sub>O TFD process type and “Other” N<sub>2</sub>O-using process types. However, inventory compilers should note that the difference in flows of unreacted input gases or by-products between process types should be taken into account when it comes to estimating the fraction of input gases or by-products that are effectively abated (i.e. when estimating the  $a_i$  and  $a_k$  values in the Tier 2a or 2b methods or the  $a_{i,p}$  and  $a_{k,p}$  values in the Tier 2c method). This is important because mass flow emissions can significantly vary between process types and because not accounting for such difference would result in an incorrect estimate of emissions when the fraction of process tools equipped with emissions control technologies is not the same for different process types. For example, C<sub>2</sub>F<sub>6</sub> input gas flows (and emissions) for chamber cleaning processes can typically be in the order of one or more litres per minute while C<sub>2</sub>F<sub>6</sub> input gas flows (and emissions) for etching processes are only typically in the order of one tenth to a few tenths of litres per minute. Thus, if no tools running C<sub>2</sub>F<sub>6</sub> chamber cleaning processes are equipped with emissions control equipment while 100% of the etching tools using C<sub>2</sub>F<sub>6</sub> are equipped with emissions control equipment in a particular facility, and if there are an equal number of tools running C<sub>2</sub>F<sub>6</sub> chamber cleaning processes and etching tools running C<sub>2</sub>F<sub>6</sub>, it would be incorrect to assume that the fraction of abated C<sub>2</sub>F<sub>6</sub> emissions ( $a_{C_2F_6}$ ) is 50% because the amount of C<sub>2</sub>F<sub>6</sub> emitted from chamber cleaning processes is typically much larger than the amount of C<sub>2</sub>F<sub>6</sub> emitted from etching processes.

In the Tier 2c method, this issue is inherently taken into account because gas consumption is apportioned by process type and because process-type-specific  $a_{i,p}$  and  $a_{k,p}$  factors can be calculated. However, notwithstanding the NF<sub>3</sub>, C<sub>3</sub>F<sub>8</sub> and N<sub>2</sub>O exceptions mentioned at the beginning of the previous paragraph, gas consumption is not apportioned by process type in the Tier 2a method and, as a result, only (process-independent)  $a_i$  and  $a_k$  values can be calculated. However, the refined Tier 2a and 2b methods do account for differences in mass flow emissions between process types through ‘gamma’ default factors ( $\gamma_i$  and  $\gamma_k$ ) that reflect the ratio of emissions of input gases  $i$  or by-products  $k$  between process types. Using  $\gamma_i$  and  $\gamma_k$  default values,  $a_i$  and  $a_k$  can be estimated by counting the number of process tools running different process types and taking the ratio of tools that are equipped with suitable emissions control technologies to the total number of tools running the different process types (see Equations 6.10 and 6.11). In this context, “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 about properly accounting for emissions control treatment of greenhouse gases.

Note that the default gamma values are highly uncertain (see Table 6.16 showing relative errors of between 100 and 400% for  $\gamma_i$  and  $\gamma_k$ ) and that using accurate gas consumption apportioning along with the Tier 2c method or a hybrid Tier 2c / Tier 3a method will greatly reduce the uncertainty of emissions estimates. Please see Box 6.3 for

an explanation about why default gamma values may be not be accurate in certain situations, and why the Tier 2c, 3a, or 3b methods are strongly encouraged.

**BOX 6.3 (NEW)****WHY DEFAULT GAMMA VALUES IN THE TIER 2A AND 2B METHODS MAY NOT BE ACCURATE IN CERTAIN SITUATIONS, AND WHY THE TIER 2C, 3A OR 3B METHODS ARE STRONGLY ENCOURAGED**

Default gamma values ( $\gamma_i$  and  $\gamma_k$ ) are used in the Tier 2a and 2b methods to account for differences in the flows or unreacted input gases  $i$  or by-products  $k$  between process types. Taking gamma values into account is necessary when an input gas is consumed (or when a by-product  $k$  is produced) by more than one process type, when the use of the input gas is not apportioned by process type, and when the number of tools equipped with emissions control technologies is not the same for different process types using the same input gas (or producing the same by-product  $k$ ). Default gamma values are 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.

Default gamma values represent industry averages but are highly variable depending on the type and generation of semiconductor manufacturing facility, and, as a result, gamma values are highly uncertain (see Table 6.16) and can be the source of large errors in emission estimates. For example, in the case of  $\leq 200\text{mm}$  facilities, Table 6.4 indicates that the default  $\gamma_i$  value for  $\text{C}_2\text{F}_6$  (IPC/EWC) is 9.24, representing that the ratio of uncontrolled emissions of  $\text{C}_2\text{F}_6$  from in-situ plasma cleaning processes (IPC) is – on average – 9.24 times higher than uncontrolled emissions of  $\text{C}_2\text{F}_6$  from etch and wafer cleaning processes (EWC). However, the actual gamma value for a particular facility may be significantly different than this default value. For instance, in the case of an ‘old’ 150mm semiconductor facility equipped with TFD tools running  $\text{C}_2\text{F}_6$ -based in-situ cleaning processes with high  $\text{C}_2\text{F}_6$  flows, the actual  $\gamma_i$  value for  $\text{C}_2\text{F}_6$  for this particular facility may be significantly higher (e.g. 50 or more) than the industry average because emissions of  $\text{C}_2\text{F}_6$  from IPC processes will be much higher than  $\text{C}_2\text{F}_6$  emissions from etching processes. Conversely, if a ‘newer’ (built more recently) 200mm facility has most of its TFD tools equipped with the  $\text{NF}_3$  remote plasma cleaning (RPC) technology and only a few TFD tools equipped with the  $\text{C}_2\text{F}_6$  in-situ plasma cleaning (IPC), then the actual  $\gamma_i$  value for  $\text{C}_2\text{F}_6$  for this particular facility will be lower than the default value of 9.24 because  $\text{C}_2\text{F}_6$  emissions from IPC processes may be of the same order of magnitude as  $\text{C}_2\text{F}_6$  emissions from EWC processes. In the case of a ‘modern’ 200mm facility is fully equipped with the  $\text{NF}_3$  RPC technology and has no tools running the  $\text{C}_2\text{F}_6$  IPC technology, then the actual IPC/EWC  $\gamma_i$  value for  $\text{C}_2\text{F}_6$  for this facility is zero, and gamma becomes irrelevant in such instance because  $\text{C}_2\text{F}_6$  consumption in that facility is not shared across more than one process type (in this example,  $\text{C}_2\text{F}_6$  would only be used for EWC processes, and the inventory compiler would not have to use a default gamma value because Equation 6.10 simplifies to  $a_i = m_{a_i}/m_i$  since  $n_{a_i}=n_i=0$ ). Also, inventory compilers should note that, in the case of a fully abated facility ( $a_i=a_k=1$ ), the uncertainty of gamma is no longer a concern since  $n_{a_k}=n_k$  and  $m_{a_k}=m_k$ .

Because actual (site-specific)  $\gamma_i$  and  $\gamma_k$  values may significantly differ from the defaults used in the Tier 2a and 2b methods, and because – as a result – the Tier 2a method may be both inaccurate and 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 or accurate apportioning model for the facility.

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## TIER 2 METHODS

### Tier 2a Method

The Tier 2a method is only applicable to the semiconductor sub-sector and is based on default emission factors calculated over all processes and substrate sizes, representing 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 Tier 2a method does not distinguish between substrate size and 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. Tier 2a should not be used for 450 mm facilities. Please see Table 6.3 for the Tier 2a default emission factors. 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 6.12) and the ratio of uncontrolled emissions of gases  $i$  and by-products  $k$  from TFD process tools to uncontrolled emissions of gases  $i$  and by-products  $k$  from EWC process tools ( $\gamma_i$ ,  $\gamma_k$  - see Table 6.4).

The Tier 2a utilization efficiency and by-product default emission factors ( $U_i$  and  $B_{k,i}$ ) represent industry averages over all semiconductor processes and substrate sizes. Hence, unlike the Tier 2b, Tier 2c and Tier 3 methods that are explained later in this section, the Tier 2a method does not distinguish between substrate sizes ( $\leq 200$  mm vs. 300 mm for the Tier 2b method), process types (EWC, RPC, IPC, TFD, and 'other' process types for the Tier 2c method), or site-specific processes (recipes or families of similar recipes for the Tier 3a method and site-specific stack emission factors for the Tier 3b method). However, the Tier 2a method provides 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  $C_3F_8$ ,  $NF_3$ , and  $N_2O$  should be apportioned between their different uses, as applicable to each reporting site.

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 ( $EAB_{i,CF_4}$ ). However, note that  $EAB_{i,CF_4}$  may be set equal to zero if the emissions control equipment manufacturer can certify that reactions between hydrocarbon fuel and  $F_2$  to form  $CF_4$  is not occurring within their emissions control systems (i.e. certify that  $AB_{i,CF_4} = 0$ ).

Because site-specific factors must be accounted for ( $C_i$ ,  $D_i$ ,  $D_k$ ,  $\eta$ ,  $a_i$ ,  $a_k$ ,  $n_{a,i}$ ,  $m_{a,i}$ ,  $n_i$ ,  $m_i$ ,  $UT$ ), inventory compilers using the Tier 2a method must have direct communication with industry to gather consumption and emissions control-related data and to ensure that emissions control technologies 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  $i$  ( $C_i$ ) 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).

$$\begin{aligned} &\text{EQUATION 6.5 (UPDATED)} \\ &\text{EMISSIONS OF INPUT GAS } i \\ &E_i = C_i \cdot (1 - U_i) \cdot (1 - D_i) \end{aligned}$$

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.

$$\begin{aligned} &\text{EQUATION 6.6 (UPDATED)} \\ &\text{BY-PRODUCT EMISSIONS} \\ &BPE_k = \sum_i [C_i \cdot B_{k,i} \cdot (1 - D_k)] \end{aligned}$$

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 per 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.

As noted in Box 6.1, 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.

When  $NF_3$  is used in remote clean process 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 remote clean 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  $<0.1\%$  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.

<p style="text-align: center;"><b>EQUATION 6.7 (NEW)</b></p> <p style="text-align: center;"><b>BY-PRODUCT EMISSIONS FROM HYDROCARBON FUELLED COMBUSTION EMISSIONS CONTROL SYSTEMS</b></p> $EAB_{i,CF_4} = C_i \cdot (1 - U_i) \cdot (1 - \eta) \cdot AB_{i,CF_4}$
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i = Input gas (i= only  $NF_3$  used in remote clean process 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 by the emissions control OEM or electronics manufacturer.

$C_i$  = Consumption of gas i (i= only  $NF_3$  used in remote clean process or  $F_2$  for the purpose of Equation 6.7).

$U_i$  = Use rate of gas i (fraction destroyed or transformed in process).

$\eta$  = 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 remote clean process or  $F_2$  for the purpose of Equation 6.7) = Mass fraction of  $NF_3$  used in remote clean process 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  $<0.1\%$ ; 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 note that the overall reductions in emissions of process gases and by-products ( $D_i$ ,  $D_k$ ) are calculated 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 ( $d_i$ ,  $d_k$ ), and the average uptime of emissions control systems (UT).



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

$$D_i = a_i \cdot d_i \cdot UT$$

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). $d_i$  = 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**  

$$D_k = a_k \cdot d_k \cdot UT$$

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 6.10). $d_k$  = 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.

When using the Tier 2a method, inventory compilers should calculate the fraction 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). In the Tier 2a method, the  $a_i$  and  $a_k$  parameters are calculated based on default ‘gamma’ factors ( $\gamma_i$  and  $\gamma_k$ ) provided in Table 6.4. As discussed in the Section on gas consumption and apportioning (in particular, see Box 6.3), taking gamma values into account is necessary when an input gas (or a by-product k) is consumed by more than one process type (denominated as process type 1 and process type 2 in Equations 6.10 and 6.11), when the use of the input gas is not apportioned between process type 1 and process type 2, and when the number of tools equipped with emissions control technologies is not the same for process type 1 and process type 2. 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 number of tools equipped with suitable emissions control technology for gas i and by-product k ( $n_{a,i}$ ,  $m_{a,i}$ ,  $n_{a,k}$ ,  $m_{a,k}$ ) and the total number of tools in the reporting facility using gas i or producing by-product k ( $n_i$ ,  $m_i$ ,  $n_k$ ,  $m_k$ ). The gamma factors are meant to reflect the ratio of uncontrolled emissions of gas i or by-product k from tools running process type 1 to the uncontrolled emissions of gas i or by-product k from tools running process type 2. Process type 1 is related to the total emission or total tool counts for the RPC, IPC, ITC, or TFD process types, while Process type 2 is EWC or “Other”. For each gas where a value for  $\gamma_i$  or  $\gamma_k$  exists, Table 6.4 defines process types 1 and 2, which should be matched with the number of tools used in Equations 6.10 and 6.11 below ( $n_i$ ,  $m_i$ ,  $n_{ai}$ ,  $m_{ai}$ ). Note that in the case of 300 mm facilities and of the  $\gamma_i$  value for  $\text{NF}_3$  and of the  $\gamma_k$  value for  $\text{CF}_4$  the tool counts for process type 1 ( $m_{ai}$  and  $m_i$ ) is defined as the sum of the tools using the in-situ plasma cleaning (IPC) and the in-situ thermal cleaning (ITC) technologies, as applicable.

**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 process type 1, and that are equipped with suitable emissions control technologies for gas i (site-specific).

$ma_i$  = Number of tools using gas i, running process type 2, 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 process type 1 (site-specific).

$m_i$  = Total number of tools using gas i and running process type 2 (site-specific).

$\gamma_i$  = Default factor reflecting the ratio of uncontrolled emissions of input gas i from tools running process type 1 to uncontrolled emissions of input gas i from process tools running process type 2 (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 process type 1, 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 process type 2, 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 process type 2 (site-specific).

$m_k$  = Total number of tools producing by-product k and running process type 2 (site-specific).

$\gamma_k$  = Default factor reflecting the ratio of uncontrolled emissions of by-product k from process tools running process type 1 to uncontrolled emissions of by-product k from process tools running process type 2 (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

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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, it is considered *good practice* to interlock process tools or to use backup emissions control systems because such practices reduce 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<sub>n</sub> = 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<sub>n</sub> = 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 only applicable to the semiconductor sub-sector and uses the same set of equations as the Tier 2a method (Equations 6.5 to 6.12), but distinct U<sub>i</sub> and B<sub>k,i</sub> emission factors are provided depending on the substrate size being manufactured (≤200 mm vs. 300 mm, see Table 6.5). As discussed in section 6.2.1, the use of the Tier 2b method over the Tier 2a method is preferred, unless it is not possible to distinguish gas consumption by substrate size (for semiconductor manufacturing facilities that process multiple substrate sizes). Hence, for facilities that manufacture only one size of substrates (≤200 mm or 300 mm), the corresponding U<sub>i</sub> and B<sub>k,i</sub> default emissions factors of Table 6.5 should be used, along with the other default factors (AB<sub>i,CF4</sub>, γ<sub>i</sub>, γ<sub>k</sub>, d<sub>i</sub>, d<sub>k</sub>, – see Equation 6.7 and Tables 6.4 and 6.12). With this distinction in mind, all other site-specific Tier 2b factors (C<sub>i</sub>, D<sub>i</sub>, D<sub>k</sub>, η, a<sub>i</sub>, a<sub>k</sub>, n<sub>a,i</sub>, m<sub>a,i</sub>, n<sub>i</sub>, m<sub>i</sub>, UT) are estimated in the same manner as for the Tier 2a method, and inventory compilers using the Tier 2b method must have direct communication with industry to gather consumption and emissions control-related data and ensure that emissions control technologies are installed and used in accordance with the guidance provided in this document.

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<sub>i</sub>), plus emissions of all by-products k (BPE<sub>k</sub>) resulting from the conversion of all input gases i used during production, plus emissions of CF<sub>4</sub> from hydrocarbon-fuel-based combustion emissions control systems (EAB<sub>i,CF4</sub>). As in the Tier 2a method, EAB<sub>i,CF4</sub> may be equalled to zero if the emissions control equipment manufacturer can certify that reactions between hydrocarbon fuel and F<sub>2</sub> to form CF<sub>4</sub> is not occurring within their emissions control system (i.e. certify that AB<sub>i,CF4</sub> = 0).

## **Tier 2C method**

The Tier 2c method is applicable to the semiconductor and display sub-sectors and is based on a set of equations allowing to account for default emission factors that are provided for distinct process types p (U<sub>i,p</sub> and B<sub>i,k,p</sub>). 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<sub>2</sub>O TFD, and 6) N<sub>2</sub>O ‘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<sub>2</sub>O TFD. 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.). Please see Tables 6.6 to 6.7 for the default  $U_{i,p}$  and  $B_{i,k,p}$  Tier 2c emission factors for the semiconductor sub-sector ( $\leq 200$  mm and 300 mm substrate sizes respectively), and Table 6.8 for the default  $U_{i,p}$  and  $B_{i,k,p}$  Tier 2c emission factors for the display 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 6.12), which are the same as for the Tier 2a and 2b methods as the DRE defaults do not depend on process type.

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 by process type, which introduces additional complexity; Please see the section on Gas Consumption and Apportioning for further detail. Because site-specific factors must be accounted for ( $C_{i,p}$ ,  $D_{i,p}$ ,  $D_{k,p}$ ,  $\eta_p$ ,  $a_{i,p}$ ,  $a_{k,p}$ ,  $UT_p$ ), inventory compilers using the Tier 2c method must have direct communication with industry to gather consumption and emissions control-related data and to ensure that emissions control technologies 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 ( $EAB_{i,CF_4}$ , which may be equalled 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), but such emissions are calculated using process-type-dependent Equations 6.13 to 6.20.

$$\text{EQUATION 6.13 (UPDATED)} \\ \text{EMISSION OF INPUT GAS I} \\ E_i = \sum_p [C_{i,p} \cdot (1 - U_{i,p}) \cdot (1 - D_{i,p})]$$

Where:

$E_i$  = Emissions of unreacted input gas  $i$  (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.

$$\text{EQUATION 6.14 (UPDATED)} \\ \text{PROCESS BY-PRODUCT EMISSIONS FROM INPUT GAS I} \\ BPE_k = \sum_i [\sum_p [C_{i,p} \cdot B_{k,i,p} \cdot (1 - D_{k,p})]]$$

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.

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As noted in Box 6.1, the formation of FC gas by-products such as CF<sub>4</sub>, C<sub>2</sub>F<sub>6</sub>, CH<sub>3</sub>F, CH<sub>2</sub>F<sub>2</sub>, and CHF<sub>3</sub> can occur when etching or cleaning carbon-containing films, even when input gases do not contain carbon (e.g. NF<sub>3</sub>, SF<sub>6</sub>, F<sub>2</sub>). However, when using NF<sub>3</sub>, SF<sub>6</sub>, F<sub>2</sub> 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<sub>4</sub> or other carbon-containing greenhouse gases are formed during the process. Thus, in such cases (and in such cases only), the B<sub>k,i,p</sub> factors may be equated to zero in Equation 6.14. 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<sub>k,i,p</sub> 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.

When NF<sub>3</sub> is used in remote clean process or F<sub>2</sub> is used as an input gas and when hydrocarbon-fuel-based combustion emissions control technology is used, direct reaction with hydrocarbon fuel and F<sub>2</sub> (including F<sub>2</sub> resulting from the decomposition of NF<sub>3</sub> in remote clean process) to form CF<sub>4</sub> can occur. Unless the emissions control equipment original equipment manufacturer (OEM) or electronics manufacturer can certify that the rate of conversion from F<sub>2</sub> to CF<sub>4</sub> or from NF<sub>3</sub> to CF<sub>4</sub> is <0.1% on a mass basis, Equation 6.15 should be used to estimate the amount of CF<sub>4</sub> produced within and emitted from the emissions control device.

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

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

Where:

i = input gas (i= only NF<sub>3</sub> used in remote clean process or F<sub>2</sub> for the purpose of Equation 6.15).

EAB<sub>i,CF<sub>4</sub></sub> = Emissions of CF<sub>4</sub> from hydrocarbon-fuel-based combustion emissions control systems when direct reaction with hydrocarbon fuel and fluorinated species is not certified by the emissions control equipment OEM or electronics manufacturer.

C<sub>i,p</sub> = Consumption of input gas i for process type p (i= only NF<sub>3</sub> used in remote clean process or F<sub>2</sub> for the purpose of Equation 6.15).

U<sub>i,p</sub> = Use rate of gas i for process p (fraction destroyed or transformed in process p).

η<sub>p</sub> = Ratio of emissions control systems connected to tools running process type p and certified not to form CF<sub>4</sub> within emissions control systems to the total number of emissions control systems running process type p in the facility (site-specific fraction).

AB<sub>i,CF<sub>4</sub></sub> (i = only NF<sub>3</sub> used in remote clean process or F<sub>2</sub> for the purpose of Equation 6.15) = Mass fraction of NF<sub>3</sub> used in remote clean process or F<sub>2</sub> in process exhaust gas that is converted into CF<sub>4</sub> by direct reaction with hydrocarbon fuel and F<sub>2</sub> gas in a combustion emissions control system. AB<sub>i,CF<sub>4</sub></sub> is set to zero if the emissions control equipment OEM or electronics manufacturer can certify that the rate of conversion from F<sub>2</sub> to CF<sub>4</sub> or from NF<sub>3</sub> to CF<sub>4</sub> is <0.1%; otherwise, a default value of AB<sub>NF<sub>3</sub>,CF<sub>4</sub></sub> = 0.093 or AB<sub>F<sub>2</sub>,CF<sub>4</sub></sub> = 0.116 should be used.

k = By-product gas.

p = Process type (remote plasma clean using NF<sub>3</sub> or any process type using F<sub>2</sub> 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<sub>i,p</sub>, D<sub>k,p</sub>) 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<sub>i,p</sub>, a<sub>k,p</sub>), the destruction removal efficiency of gas i and by-product k (d<sub>i</sub>, d<sub>k</sub>), and the average uptime of emissions control systems connected to process tools running process type p (UT<sub>p</sub>).

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

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

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).

$d_i$  = 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**

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

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).

$d_k$  = 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.

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 ( $na_{i,p}$ ) 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.

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

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

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).

$na_{i,p}$  = 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<sub>4</sub> 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**

$$a_{k,p} = \sum_i \frac{ma_{k,p}}{m_{k,p}}$$

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).

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

$m_{k,p}$  = 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, it is considered *good practice* to interlock process tools or to use backup emissions control systems because such practices reduce uncertainty by eliminating the need to estimate  $UT_p$  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 greenhouse gases (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  $C_2F_6$ . 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



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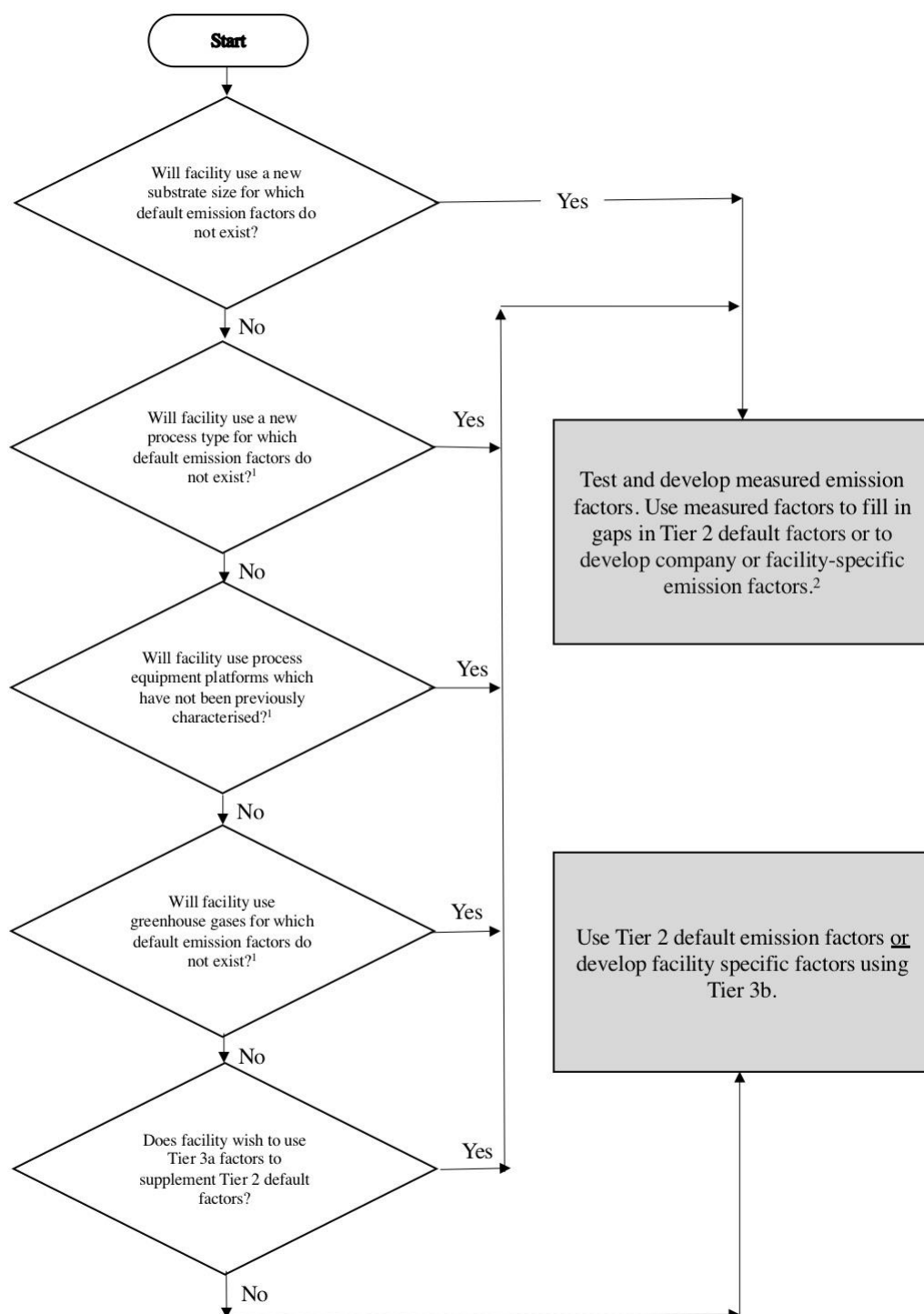
hybrid method when the new gas and process type combination accounts for 1% or more of facility GHG consumption by mass.

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. Although country-specific default emission factors are less desired, 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. Country-specific emission factors are less desired because a technological change in a particular country would likely quickly diffuse in other countries, and refining default emission factors should be encouraged at the global 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 (still to be designed at the time of writing of this *2019 Refinement*) allowing protection of the underlying confidential nature of the information. The IPCC Tier 2 default factors should be updated based on a finding by experts that current Tier 2 factors are no longer representative.

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% of total gas used in year 2; 25% in year 3; 10% in year 4; and 0% 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.

1187 **Figure 6.2 (new) Decision tree to determine need for measured emission factors**



1188 Note:

1189 1. If a new gas and process combination are used that accounts for less than 1% of facility fluorinated GHG consumption by mass and (1-U)

1190 is not measured or not listed, reporter may assume (1-U) = 0.8, B<sub>CF4</sub> = 0.15, B<sub>C2F6</sub> = 0.05.

1191 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 parameters

The Tier 3a method 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. As discussed above, 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 fab. 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  $(1-U_{i,p})$  and  $B_{k,i,p}$  emission factors in Equations 6.13 to 6.15 and 6.18 to 6.19 are measured for ‘recipes’, i.e., specific combinations of process conditions (e.g. gas flows, plasma power, pressure, temperature, duration) and technologies used to etch patterns onto electronics devices, to clean film deposition chambers, or to deposit films on substrate or for sets 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 centreline recipe can be used to establish Tier 3a emission factors for each set of similar recipes. Recipes are deemed ‘similar’ when the centreline process can reasonably be deemed representative of facility-specific process conditions, of the potential variability of such process conditions around the centreline process during normal manufacturing operations, and when the substrate size, process type/subtype, tool platform, film type (e.g.  $\text{SiO}_x\text{N}_y$ ,  $\text{Si}_x\text{N}_y$ ), and input process gas 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 top 75% of total process greenhouse gas usage in kg and the top 50% of emissions in kg  $\text{CO}_2\text{e}$ );
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 3 measurements are made, the reporting facility should document the following:

- Date measurements were made;
- Industry type (semiconductor, MEMs, PV and display);
- Substrate size;
- Process type (etching, TFD);
- Film type (e.g. carbon containing film,  $\text{SiO}_x\text{N}_y$ ,  $\text{Si}_x\text{N}_y$ );
- Tool manufacturer, platform and model/chamber name;
- Process conditions (e.g. gas flow, pressure, temperature, power);
- Input gases;
- 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 or emissions control equipment emission factors that have been measured by the reporting facility(ies), 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 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 a fluorinated compound (FC-) or  $\text{N}_2\text{O}$ -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 while, 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 also 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.

### Ranking Stacks for Testing

It is *good practice* to test as many stack systems as practicable, including the highest-emitting stack systems that cumulatively represent a minimum of 85% of total facility CO<sub>2</sub>-equivalent emissions. To rank stack systems by their expected contribution to total emissions, use Equations 6.21, 6.22 and 6.23 along with the default emissions factors found in the Tier 2a method for the semiconductor and display sub-sectors or the Tier 2b method (semiconductor only), depending upon whether more than one wafer size is manufactured (semiconductor only). Consumption data from the previous year may be used for this preliminary estimate.

<p style="text-align: center;"><b>EQUATION 6.21 (NEW)</b></p> <p style="text-align: center;"><b>PRELIMINARY ESTIMATE OF STACK PROCESS GAS EMISSIONS</b></p> $E_{i,s} = C_{i,s} \cdot (1 - U_i) \cdot (1 - (a_{i,s} \cdot d_i \cdot UT_s)) \cdot GWP_i$
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Where:

$E_{i,s}$  = Annual emissions of input gas i from stack system s (kg CO<sub>2</sub>e).

$C_{i,s}$  = Amount of input gas i consumed for stack system s (kg). When determining  $C_{i,s}$  it is possible to simplify gas usage for stack system s by the ratio of tools using gas i connected to the stack system and the total number of tools in facility f using gas i and/or using engineering process knowledge such as wafer throughput to estimate gas usage.

$U_i$  = Use rate of gas i (fraction destroyed or transformed).

$a_{i,s}$  = Estimate of the fraction of gas i emitted from process tools connected to stack system s and equipped with suitable emissions control technologies used in processes with emissions control technologies (site-specific fraction, determined in Equation 6.10 as applied to stack system s).

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

$UT_s$  = Average uptime factor of all emissions control systems connected to process tools connected to stack system s (site-specific fraction, determined by Equation 6.12 as applied to stack system s).

$GWP_i$  = Global Warming Potential of gas i (kg CO<sub>2</sub>e/ kg gas i).

i = Input gas.

s = Stack system.

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**EQUATION 6.22 (NEW)**  
**PRELIMINARY ESTIMATE OF BY-PRODUCT EMISSIONS FROM STACKS**

$$BE_{k,i,s} = C_{i,s} \cdot B_{k,i} \cdot (1 - (a_{k,s} \cdot d_k \cdot UT_s)) \cdot GWP_k$$

Where:

$BE_{k,i,s}$  = Annual emissions of by-product k formed from input gas i for stack system s (kgCO<sub>2</sub>e).

$C_{i,s}$  = Amount of input gas i consumed for stack system s (kg). When determining  $C_{i,s}$  it is possible to simplify gas usage for stack system s by the ratio of tools using gas i connected to the stack system and the total number of tools in facility f using gas i and/or using engineering process knowledge such as wafer throughput to estimate gas usage.

$B_{k,i}$  = Emission factor for by-product k generated from input gas i (kg of by-product k created per kg of gas i consumed).

$a_{k,s}$  = Estimate of the fraction of by-product k emitted from process tools connected to stack system s and equipped with emissions control technologies (site-specific fraction, determined by Equation 6.11 as applied to stack system s).

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

$UT_s$  = Average uptime factor of all emissions control systems connected to process tools connected to stack system s (site-specific fraction, determined by Equation 6.12 as applied to stack system s).

$GWP_k$  = Global Warming Potential of by-product k (kg CO<sub>2</sub>e/ kg by-product k).

i = Input gas.

k = By-product gas.

s = Stack system.

Inventory compilers should calculate, for each reporting site, the average uptime of all emissions control equipment systems connected to process tools on stack system s ( $UT_s$ ), using Equation 6.23. To this end, inventory compilers should account for the total time ( $Td_{n,s}$ ) that any emissions control equipment n connected to process tool(s) on stack system s in the reporting facility 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 ( $TT_{n,s}$ ) 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. 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  $UT_s$  may be set to one (1) if suitable backup emissions control equipment or interlocking with the process tool is implemented for each emissions control equipment. Thus, it is considered *good practice* to interlock process tools or to use backup emissions control equipment because such practices reduce uncertainty by eliminating the need to estimate  $UT_s$  for the reporting facility.

**EQUATION 6.23 (NEW)**  
**UPTIME OF EMISSIONS CONTROL SYSTEMS**

$$UT_s = 1 - \frac{\sum_n Td_{n,s}}{\sum_n TT_{n,s}}$$

Where:

$UT_s$  = Average uptime of all emissions control equipment connected to process tools on stack system s (site-specific fraction).

$T_{d,n,s}$  = Total time that emissions control equipment  $n$  connected to process tools on stack system  $s$  in the facility is not in operational mode when at least one of the manufacturing tools connected to emissions control equipment  $n$  is in operation (minutes per year).

$TT_{n,s}$  = Total time during which emissions control system  $n$  connected to stack system  $s$  has at least one associated manufacturing tool in operation (minutes per year).

## Testing Frequency

Reporting facilities using the Tier 3b method should test major stacks emitting greenhouse gases (GHGs) on an annual basis. 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. 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) Annual consumption of a FC gases or  $N_2O$  used during the most recent emissions test (expressed in  $CO_2e$ ) changes by more than 10 percent of the total annual FC gases and  $N_2O$  consumption, relative to gas consumption in  $CO_2e$  for that gas during the year of the most recent emissions test (for example, if the use of a single gas goes from 25 percent of total gas consumption to greater than 35 percent of total gas consumption, this change would trigger a re-test).
- (ii) A change in the consumption of a GHG that was not used during the emissions test and not reflected in the facility-specific emission factor
- (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.
- (v) A stack system that formerly met the criteria specified for not being subject to testing no longer meets those criteria.

## 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 6.9, or their equivalents. In addition, inventory compilers should measure the facility-specific consumption of each FC gas and  $N_2O$ , as well as emissions and consumption of each FC and  $N_2O$  according to the following steps:

- Measurements of total gas flow rate up the stack on the test day using EPA Method 1 or 2 or an equivalent method should be conducted.
- Measurements of 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 should be conducted.
- 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 the inventory compiler should ensure that minimal 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 fluorinated gases known to be used by the facility and any possible fluorinated greenhouse gas by-products. If an expected by-product or known used gas is not detected, a stack concentration corresponding to  $\frac{1}{2}$  the field detection limit (FDL) should be assumed.  $CF_4$ ,  $C_2F_6$ ,  $C_3F_8$ ,  $C_4F_6$ ,  $c-C_4F_8$ ,  $C_5F_8$ ,  $CHF_3$ ,  $CH_2F_2$ , and  $CH_3F$  are expected by-products that should all be targeted for measurement.
- If a gas is added to use in the facility at a time after a stack testing has been conducted, emissions should be re-estimated using the Tier 2a or Tier 2b, methods for the reporting year.
- The amount of each FC 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

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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 fluorinated GHG).

- If consumption of an FC gas is too low to be accurately measured during the testing period, then the testing period in order to account for usage should be increased or consumption from pro-rated long-term consumption data may be calculated. Calculating Emissions

Inventory compilers should calculate the emissions of each FC gas and N<sub>2</sub>O consumed as an input gas using Equation 6.24 and each fluorinated greenhouse gas formed as a by-product using Equation 6.25. 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 6.24 or Equation 6.25.

**EQUATION 6.24 (NEW)**  
**TOTAL FLUORINATED GHG INPUT GAS EMITTED FROM STACK SYSTEM DURING SAMPLING PERIOD**

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

Where:

ES<sub>i,s</sub> = Emissions of input gas i from stack system s during the sampling period (kg).

MW<sub>i</sub> = Molecular weight of gas i (g/g-mole).

Q<sub>s</sub> = Flow rate of stack system s during the sampling period (m<sup>3</sup>/min).

SV = Standard molar volume of gas (0.0240 m<sup>3</sup>/g-mole at 68°F and 1 atm.).

X<sub>i,s,m</sub> = Average concentration of input gas i in stack system s during time interval m (ppbv).

Δt<sub>m</sub> = 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<sup>3</sup> = 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 6.25 (NEW)**  
**TOTAL FLUORINATED GHG BY-PRODUCT EMITTED FROM STACK SYSTEM DURING SAMPLING PERIOD**

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

Where:

ES<sub>k,s</sub> = Emissions of by-product k emitted from stack system s during the sampling period (kg).

MW<sub>k</sub> = Molecular weight of by-product gas k (g/g-mole).

Q<sub>s</sub> = Flow rate of stack system s during the sampling period (m<sup>3</sup>/min).

SV = Standard molar volume of gas (0.0240 m<sup>3</sup>/g-mole at 68 °F and 1 atm.).

X<sub>k,s,m</sub> = Average concentration of by-product k in stack system s during time interval m (ppbv).

Δt<sub>m</sub> = 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<sup>3</sup> = 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 from the results of the stack testing, inventory compilers should use the following guidance and the accompanying requirements of recognized maximum field detection limits (FDLs) as detailed in Table 6.10. Field detection limits for instrumentation used in stack testing should not exceed those depicted in Table 6.10

- a. If an FC gas or N<sub>2</sub>O is consumed during the sampling period, but its emissions are not detected, a stack concentration corresponding to ½ the field detection limit (FDL) as listed in Table 6.10 or the actual FDL determined for the target compound for the value of X<sub>i,s,m</sub> in Equation 6.24 or X<sub>k,s,m</sub> in Equation 6.25 should be assumed.
- b. If an FC gas or N<sub>2</sub>O is consumed during the sampling period but only detected intermittently during the sampling period, the detected concentration for the value of X<sub>i,s,m</sub> in Equation 6.24 should be assumed when available, or a concentration corresponding to one-half of the FDL determined for the target compound for the value of X<sub>i,s,m</sub> may be assumed when the target compound is not detected.
- c. If an FC gas or N<sub>2</sub>O is not consumed during the sampling period and when it is an expected by-product not detected during the sampling period, a concentration corresponding to one-half of the FDL determined for the target compound for the value of X<sub>k,s,m</sub> in Equation 6.25 should be assumed.
- d. If an FC gas or N<sub>2</sub>O is not consumed during the sampling period and when it is a possible by-product gas that is not detected during the sampling period, then inventory compilers may assume that emissions for the target compound for the tested stack system are zero.

After calculating ES<sub>i,s</sub> and ES<sub>k,s</sub>, inventory compilers should calculate a facility-specific emission factor for each input gas consumed (in kg of FC gas or N<sub>2</sub>O emitted per kg of input gas i consumed) in the tools that vent to stack systems that are tested, as applicable, using Equation 6.26 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<sub>i,s</sub> 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 6.27 of this section.

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

Where:

EF<sub>i,f</sub> = 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<sub>i,s</sub> = Emissions of input gas i from stack system s during the sampling period (kg).

θ = Fraction of total fab emissions included in the tested stacks based on preliminary estimates (site-specific fraction). If preliminary estimates show that the stack testing should account for 85% of total emissions, then θ is equal to 0.85.

Activity<sub>i,f</sub> = Consumption of input gas i for facility f during the stack testing period (kg).

UT<sub>f</sub> = Total uptime of all emissions control systems for facility f during the sampling period, as calculated in Equation 6.30 (site-specific fraction).

a<sub>i,f</sub> = 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<sub>i</sub> = Destruction Removal Efficiency (DRE) for gas i (fraction).

i = Input gas.

s = Stack system.

f = Facility.



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After calculating  $EF_{i,f}$ , inventory compilers should calculate a facility-specific emission factor for each by-product  $k$  (in kg of by-product  $k$  per kg of total input gases  $i$  consumed) in the tools vented to stack systems that are tested, as applicable, using Equation 6.27 of this section. When calculating the by-product emission factor for an 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 6.27 (NEW)**  
**BY-PRODUCT SPECIFIC EMISSION FACTOR**

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

Where:

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

$ES_{k,s}$  = Emissions of fluorinated GHG by-product gas  $k$ , emitted from stack system  $s$  during the sampling period (kg).

$\theta$  = Fraction of total fab emissions included in the tested stacks based on preliminary estimates (site-specific fraction). If preliminary estimates show that the stack testing should account for 85% of total emissions, then  $\theta$  is equal to 0.85.

$Activity_{i,f}$  = Consumption of input gas  $i$  for facility  $f$  during the stack testing 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 by-product  $k$  (fraction).

$i$  = Input gas.

$k$  = 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 6.28.

**EQUATION 6.28 (NEW)**  
**ANNUAL EMISSION OF GAS I**

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

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 6.30 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 by-product k formed using Equation 6.29 of this section.

**EQUATION 6.29 (NEW)**  
**ANNUAL EMISSION OF BY-PRODUCT K**

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

Where:

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

$EF_{k,f}$  = Emission factor for 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 input gases consumed).

$C_{i,f}$  = Total consumption of 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 6.30 of this section (fraction).

$a_{k,f}$  = Estimate of the fraction of by-product gas k emitted from process tools equipped with suitable emissions control technologies (site-specific fraction, as determined in Equation 6.10) for facility f.

$d_k$  = Destruction Removal Efficiency (DRE) for gas k (fraction).

i = Input gas.

k = 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 6.30. 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 6.26 and Equation 6.27. 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 equipment. Thus, it is considered *good practice* to interlock process tools or to use backup emissions control equipment because such practices reduce uncertainty by eliminating the need to estimate  $UT_f$  for the reporting facility. Facility records such as maintenance records for emissions control systems can also be used to estimate emissions control system uptime.

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**EQUATION 6.30 (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 6.25 and 6.26, 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. For determining the amount of tool operating time, facilities 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, facilities should prorate the operating time to account for the days in which the tool was not installed; 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 there was at least one tool installed at all times throughout the year. If the facility has tools that are idle with no gas flow through the tool, inventory compilers may calculate total tool time using the actual time that gas is flowing through the tool.

n = Emissions control system

f = Facility.

### 6.2.1.2 FLUORINATED LIQUIDS

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

Unweighted fluorinated liquid emissions consist primarily of perfluorinated amines, hydrofluoroethers, perfluoropolyethers, 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 liquid FC materials may be regulated in some regions (e.g., as volatile organic compounds) and this should be considered when choosing alternative fluorinated liquids.

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. 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 s globally (see Table 6.13). 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<sup>2</sup>)). The result is a set of annual emissions estimates expressed in kg of materials emitted during the manufacture of that 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 6.31.

**EQUATION 6.31 (UPDATED)**  
**TIER 1 METHOD FOR ESTIMATION OF TOTAL FC EMISSIONS FROM FLUORINATED LIQUIDS**  
$$FC_i = EF_i \cdot P$$

Where:

$FC_i$  = Emissions of fluorinated liquid  $i$  (kg).

$EF_i$  = Emission factor for fluorinated liquid aggregate emissions per  $m^2$  of substrate consumed during the period (kg/ $m^2$ ).

$P$  = 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.

**TIER 2 METHOD – FLUORINATED LIQUIDS**

There is one Tier 2 method for estimating actual emissions from the use of each fluorinated liquid. This method is a mass-balance approach that accounts for fluorinated liquid usage over an annual period. It is appropriate when company-specific data are available. 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. The company should provide the chemical composition of the fluid(s) for which emissions are estimated.<sup>3</sup> The method is expressed in Equation 6.32.

**EQUATION 6.32 (UPDATED)**  
**TIER 2 METHOD FOR ESTIMATION OF FC EMISSIONS FROM FLUORINATED LIQUIDS**

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

Where:

$FC_i$  = Emissions of fluorinated liquid  $i$  (kg).

$\rho_i$  = 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).

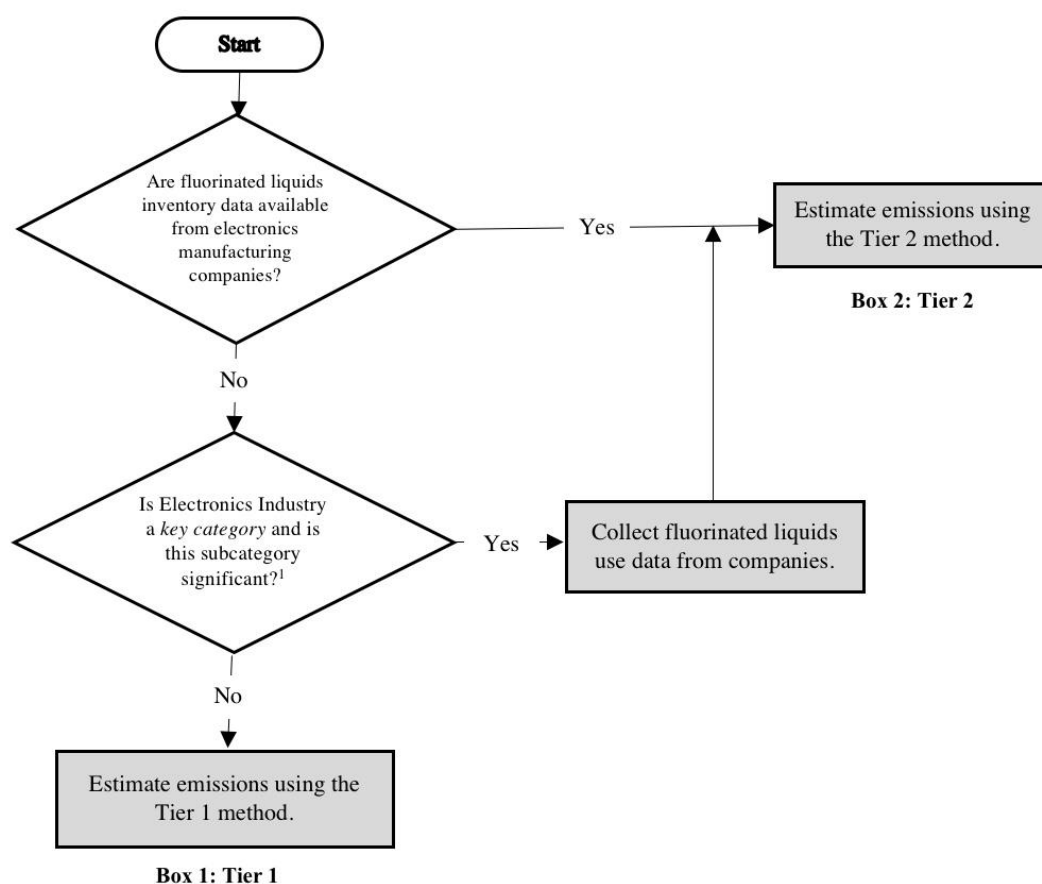
$I_{i,t}$  = Inventory of liquid  $FC_i$  in containers other than equipment at the end of the reporting year (litres in stock or storage).

$D_{i,t}$  = 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.

<sup>3</sup> In the absence of GWP estimates, the appropriate GWP for  $C_6F_{14}$  has been used as a proxy; see [http://yosemite.epa.gov/oar/globalwarming.nsf/UniqueKeyLookup/RAMR69v523/\\$File/05industrial.pdf](http://yosemite.epa.gov/oar/globalwarming.nsf/UniqueKeyLookup/RAMR69v523/$File/05industrial.pdf) at footnote to Table 4-58, page 166.

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**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.

## 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 6.2 to 6.13) 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) and World Semiconductor Council (2011, 2012, 2014 and 2016).

In the case where a new input gas is used for which no default emission factor ( $U_i$ ) 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  $B_{CF_4,i}=0.15$  and  $B_{C_2F_6,i}=0.05$ . 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% of the facility's GHG consumption by mass.

### 6.2.2.1 ETCHING AND TFT CLEANING FOR SEMICONDUCTORS, LIQUID CRYSTAL DISPLAYS, AND PHOTOVOLTAICS

#### TIER 1

The default emission factors for the Tier 1 method are presented in Table 6.2 below.

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 6.2. 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<sub>4</sub> to estimate the emissions of CF<sub>4</sub> from semiconductors and combine it with the results of other gases from a Tier 2 or Tier 3 method. It should be also noted that the Tier 1 C emission factors presented in Table 6.2 should not be used for any purpose other than estimating annual process gas-aggregate emissions from semiconductor, display 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. The Tier 1 emission factors for the display sub-sector was provided by the World Display device Industry Cooperation Committee.

TABLE 6.2 (UPDATED)												
TIER 1 GAS-SPECIFIC EMISSION FACTORS FOR PROCESS GHG EMISSIONS FROM ELECTRONICS MANUFACTURING												
Electronics industry subsector	CF <sub>4</sub>	C <sub>2</sub> F <sub>6</sub>	C <sub>3</sub> F <sub>8</sub>	C <sub>4</sub> F <sub>6</sub>	c-C <sub>4</sub> F <sub>8</sub>	C <sub>4</sub> F <sub>8</sub> O	C <sub>5</sub> F <sub>8</sub>	CHF <sub>3</sub>	CH <sub>2</sub> F <sub>2</sub>	NF <sub>3</sub>	SF <sub>6</sub>	N <sub>2</sub> O
Semiconductors, kg/m <sup>2</sup>	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 <sup>2</sup>	0.65				0.001			0.0024		1.29	4.14	17.06
PV, g/m <sup>2</sup>	5	0.2										
MEMS, kg/m <sup>2</sup>	0.015				0.076						1.86	

#### TIER 2

The default emission factors for the Tier 2 methods are presented in Tables 6.3 to 6.8 and Table 6.12 below.

Note that F<sub>2</sub> and COF<sub>2</sub> 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<sub>2</sub> and COF<sub>2</sub> for chamber cleaning can lead to the formation of CF<sub>4</sub> and other high-GWP by-products, but no data was available to derive emission factors for these gases. Note also that, although COF<sub>2</sub> is a known by-product of cleaning processes of TFD chamber using fluorinated carbon gases (e.g. CF<sub>4</sub>, C<sub>2</sub>F<sub>6</sub>, etc.), no by-product factor for COF<sub>2</sub> (i.e. B<sub>COF<sub>2</sub>,i</sub>) was included in the Tier 2 default tables due to the low GWP (~1) and short atmospheric life of COF<sub>2</sub>.

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<b>TABLE 6.3 (UPDATED)</b> <b>TIER 2A METHOD – DEFAULT EMISSION FACTORS FOR GHG EMISSIONS FROM SEMICONDUCTOR MANUFACTURING</b>																			
Process Gas	CF <sub>4</sub>	C <sub>2</sub> F <sub>6</sub>	C <sub>3</sub> F <sub>8</sub>	C <sub>3</sub> F <sub>8</sub> Remote	C <sub>4</sub> F <sub>6</sub>	c-C <sub>4</sub> F <sub>8</sub>	C <sub>4</sub> F <sub>8</sub> O	C <sub>5</sub> F <sub>8</sub>	CHF <sub>3</sub>	CH <sub>2</sub> F <sub>2</sub>	CH <sub>3</sub> F	C <sub>2</sub> HF <sub>5</sub>	NF <sub>3</sub> Remote	NF <sub>3</sub>	SF <sub>6</sub>	N <sub>2</sub> O TFD	N <sub>2</sub> O other	COF <sub>2</sub>	F <sub>2</sub>
(1-U <sub>i</sub> )	0.74	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 <sub>CF4</sub>	NA	0.19	0.2	NA	0.06	0.099	0.13	0.052	0.082	0.061	0.028	0.077	0.034	0.067	0.12	NA	NA	NM	NM
B <sub>C2F6</sub>	0.042	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 <sub>C3F8</sub>	NA	NA	NA	NA	NA	NA	NA	0.000055	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B <sub>C4F6</sub>	0.00057	NA	NA	NA	NA	0.0015	NA	NA	0.00003	NA	0.0011	NA	NA	NA	NA	NA	NA	NA	NA
B <sub>C4F8</sub>	0.0013	NA	NA	NA	0.0051	NA	NA	NA	0.0002	0.071	0.0065	NA	NA	NA	NA	NA	NA	NA	NA
B <sub>C5F8</sub>	0.00047	NA	NA	NA	NA	0.0035	NA	NA	0.00081	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B <sub>CH3F</sub>	0.002	NA	0*	NA	0.00064	0.0004	NA	NA	0.0011	0.0043	NA	NA	NA	0.0021	0.0009	NA	NA	NA	NA
B <sub>CH2F2</sub>	0.0054	NA	NA	NA	0.00003	0.00026	NA	NA	0.00077	NA	0.0021	NA	NA	0.00023	0.0000021	NA	NA	NA	NA
B <sub>CHF3</sub>	0.041	0.002	0.0000012	NA	0.018	0.022	NA	0.0053	NA	0.057	0.015	NA	NA	0.0067	0.0014	NA	NA	NA	NA
* < 1e-7 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% of facility fluorinated GHG consumption by mass and (1-U) is NM or not listed, reporter may assume (1-U) = 0.8, B <sub>CF4</sub> = 0.15, B <sub>C2F6</sub> = 0.05.																			

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TABLE 6.4 (NEW)										
TIER 2A & 2B METHODS – DEFAULT FACTORS FOR $\gamma_i$ AND $\gamma_k$ FOR SEMICONDUCTOR MANUFACTURING										
GAS (PROCESS TYPE 1/ PROCESS TYPE 2)	CF <sub>4</sub> (IPC / EWC)	CF <sub>4</sub> (RPC / EWC)	CF <sub>4</sub> ((IPC+ITC) / EWC)	C <sub>2</sub> F <sub>6</sub> (IPC / EWC)	C <sub>3</sub> F <sub>8</sub> (RPC / EWC)*	c-C <sub>4</sub> F <sub>8</sub> (IPC / EWC)	NF <sub>3</sub> (IPC / EWC)	NF <sub>3</sub> ((IPC+ITC) / EWC)	SF <sub>6</sub> (IPC / EWC)	N <sub>2</sub> O (TFD / Other)
$\gamma_i$ ( $\leq 200$ mm wafer size)	13.3	NA	NA	9.24	NA	3.37	2.77	NA	10.7	47.8
$\gamma_k$ ( $\leq 200$ mm wafer size)	13.3	NA	NA	9.24	NA	NA	NA	NA	NA	NA
$\gamma_i$ (300 mm wafer size)	17.5	NA	NA	2.57	NA	NA	NA	26.0	NA	2.35
$\gamma_k$ (300 mm wafer size)	NA	NA	NA	NA	10.4	NA	NA	NA	NA	NA
* Value estimated by analogy.										



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**TABLE 6.5 (NEW)**  
**TIER 2B METHOD – DEFAULT EMISSION FACTORS FOR GHG EMISSIONS FROM SEMICONDUCTOR MANUFACTURING**

Process Gas	CF <sub>4</sub>	C <sub>2</sub> F <sub>6</sub>	C <sub>3</sub> F <sub>8</sub>	C <sub>3</sub> F <sub>8</sub> Remote	C <sub>4</sub> F <sub>6</sub>	c-C <sub>4</sub> F <sub>8</sub>	C <sub>4</sub> F <sub>8</sub> O	C <sub>5</sub> F <sub>8</sub>	CHF <sub>3</sub>	CH <sub>2</sub> F <sub>2</sub>	CH <sub>3</sub> F	C <sub>2</sub> HF <sub>5</sub>	NF <sub>3</sub> Remote	NF <sub>3</sub>	SF <sub>6</sub>	N <sub>2</sub> O TFD	N <sub>2</sub> O other	COF <sub>2</sub>	F <sub>2</sub>
<b>≤200 mm wafer size</b>																			
(1-U <sub>i</sub> )	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 <sub>CF4</sub>	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 <sub>C2F6</sub>	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 <sub>C3F8</sub>	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B <sub>C5F8</sub>	0.00077	NA	NA	NA	NA	0.00043	NA	NA	0.0012	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B <sub>CHF3</sub>	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
<b>300 mm wafer size</b>																			
(1-U <sub>i</sub> )	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 <sub>CF4</sub>	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 <sub>C2F6</sub>	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 <sub>C3F8</sub>	NA	NA	NA	NA	NA	NA	NA	0.00012	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B <sub>C4F6</sub>	0.0015	NA	NA	NA	NA	0.008	NA	NA	0.0001	NA	0.0012	NA	NA	NA	NA	NA	NA	NA	NA
B <sub>C4F8</sub>	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 <sub>CH3F</sub>	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 <sub>CH2F2</sub>	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 <sub>CHF3</sub>	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
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% of facility fluorinated GHG consumption by mass and (1-U) is NM, reporter may assume (1-U) = 0.8, B <sub>CF4</sub> = 0.15, B <sub>C2F6</sub> = 0.05.																			

<b>TABLE 6.6 (NEW)</b> <b>TIER 2C METHOD (<math>\leq 200</math> MM) – DEFAULT EMISSION FACTORS FOR GHG EMISSIONS FROM SEMICONDUCTOR MANUFACTURING</b>																	
Process Gas	CF <sub>4</sub>	C <sub>2</sub> F <sub>6</sub>	C <sub>3</sub> F <sub>8</sub>	C <sub>4</sub> F <sub>6</sub>	c-C <sub>4</sub> F <sub>8</sub>	C <sub>4</sub> F <sub>8</sub> O	C <sub>5</sub> F <sub>8</sub>	CHF <sub>3</sub>	CH <sub>2</sub> F <sub>2</sub>	CH <sub>3</sub> F	C <sub>2</sub> HF <sub>5</sub>	NF <sub>3</sub>	SF <sub>6</sub>	N <sub>2</sub> O TFD	N <sub>2</sub> O other	COF <sub>2</sub>	F <sub>2</sub>
<b>Etching or Wafer Cleaning (EWC)</b>																	
(1-U <sub>i</sub> )	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 <sub>CF4</sub>	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 <sub>C2F6</sub>	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 <sub>C5F8</sub>	0.0012	NA	NA	NA	0.0086	NA	NA	0.0012	NA	NA	NA	NA	NA	NA	NA	NA	NA
B <sub>CHF3</sub>	0.09	0.047	NA	0.066	0.04	NA	0.0039	NA	0.049	NA	NA	NA	0.0012	NA	NA	NA	NA
<b>Remote Plasma Cleaning (RPC)</b>																	
(1-U <sub>i</sub> )	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.028	NA	NA	NA	NA	NA
B <sub>CF4</sub>	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.015	NA	NA	NA	NA	NA
<b>In-situ Plasma Cleaning (IPC)</b>																	
(1-U <sub>i</sub> )	0.92	0.55	0.4	NA	0.1	0.14	NA	NA	NA	NA	NA	0.18	NM	NA	NA	NM	NA
B <sub>CF4</sub>	NA	0.21	0.2	NA	0.11	0.13	NA	NA	NA	NA	NA	0.14	NM	NA	NA	NM	NA
B <sub>C2F6</sub>	NA	NA	NA	NA	NA	0.045	NA	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA
<b>Thin Film Deposition (TFD)</b>																	
(1-U <sub>i</sub> )	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1.0	NA	NA	NA
<b>Other</b>																	
(1-U <sub>i</sub> )	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1.0	NA	NA
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% of facility fluorinated GHG consumption by mass and (1-U) is NM, reporter may assume (1-U) = 0.8, B <sub>CF4</sub> = 0.15, B <sub>C2F6</sub> = 0.05.																	

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**TABLE 6.7 (NEW)**  
**TIER 2C METHOD (300 MM) – DEFAULT EMISSION FACTORS FOR GHG EMISSIONS FROM SEMICONDUCTOR MANUFACTURING**

Process Gas	CF <sub>4</sub>	C <sub>2</sub> F <sub>6</sub>	C <sub>3</sub> F <sub>8</sub>	C <sub>4</sub> F <sub>6</sub>	c-C <sub>4</sub> F <sub>8</sub>	C <sub>5</sub> F <sub>8</sub>	CHF <sub>3</sub>	CH <sub>2</sub> F <sub>2</sub>	CH <sub>3</sub> F	NF <sub>3</sub>	SF <sub>6</sub>	N <sub>2</sub> O TFD	N <sub>2</sub> O other	COF <sub>2</sub>	F <sub>2</sub>
<b>Etching and Wafer Cleaning (EWC)</b>															
(1-U <sub>i</sub> )	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 <sub>CF4</sub>	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 <sub>C2F6</sub>	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 <sub>C3F8</sub>	NA	NA	NA	NA	NA	0.00012	NA	NA	NA	NA	NA	NA	NA	NA	NA
B <sub>C4F6</sub>	0.0015	NA	NA	NA	0.0083	NA	0.0001	NA	0.0012	NA	NA	NA	NA	NA	NA
B <sub>C4F8</sub>	0.0033	NA	NA	0.0051	NA	NA	0.00067	0.072	0.007	NA	NA	NA	NA	NA	NA
B <sub>CH3F</sub>	0.0053	NA	0.00073	0.00065	0.0022	NA	0.037	0.0044	NA	0.008	0.0082	NA	NA	NA	NA
B <sub>CH2F2</sub>	0.014	NA	NA	0.00003	0.0014	NA	0.0026	NA	0.0023	0.00086	0.00002	NA	NA	NA	NA
B <sub>CHF3</sub>	0.013	NA	0.012	0.017	0.03	0.0069	NA	0.057	0.0016	0.025	0.0039	NA	NA	NA	NA
<b>Remote Plasma Cleaning (RPC)</b>															
(1-U <sub>i</sub> )	NA	NA	0.063	NA	NA	NA	NA	NA	NA	0.018	NA	NA	NA	NA	NA
B <sub>CF4</sub>	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.038	NA	NA	NA	NA	NA
<b>In-situ Plasma Cleaning (IPC)</b>															
(1-U <sub>i</sub> )	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.2	NA	NA	NA	NA	NA
B <sub>CF4</sub>	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.037	NA	NA	NA	NA	NA
<b>In-situ Thermal Cleaning (ITC)</b>															
(1-U <sub>i</sub> )	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.28	NA	NA	NA	NA	NA
B <sub>CF4</sub>	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.01	NA	NA	NA	NA	NA
<b>TFD</b>															
(1-U <sub>i</sub> )	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.5	NA	NA	NA
<b>Other</b>															
(1-U <sub>i</sub> )	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1.0	NA	1.0
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% of facility fluorinated GHG consumption by mass and (1-U) is NM, reporter may assume (1-U) = 0.8, B <sub>CF4</sub> = 0.15, B <sub>C2F6</sub> = 0.05.															

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<b>TABLE 6.8 (UPDATED)</b>						
<b>TIER 2C METHOD – DEFAULT EMISSION FACTORS FOR GHG EMISSIONS FROM DISPLAY MANUFACTURING</b>						
<b>Process Gas</b>	<b>CF<sub>4</sub></b>	<b>c-C<sub>4</sub>F<sub>8</sub></b>	<b>CHF<sub>3</sub></b>	<b>NF<sub>3</sub></b>	<b>SF<sub>6</sub></b>	<b>N<sub>2</sub>O</b>
<b>Etching</b>						
<b>(1-U<sub>i</sub>)</b>	0.6	0.1	0.2	0.11	0.3	NA
<b>B<sub>CF4</sub></b>	NA	0.009	0.07	NA	NA	NA
<b>B<sub>C2F6</sub></b>	NA	NA	0.05	NA	NA	NA
<b>B<sub>CHF3</sub></b>	NA	0.02	NA	NA	NA	NA
<b>Remote plasma cleaning (RPC)</b>						
<b>(1-U<sub>i</sub>)</b>	NA	NA	NA	0.03	NA	NA
<b>In-situ plasma cleaning (IPC)</b>						
<b>(1-U<sub>i</sub>)</b>	NA	NA	NA	0.3	0.9	NA
<b>Thin film deposition (TFD)</b>						
<b>(1-U<sub>i</sub>)</b>	NA	NA	NA	NA	NA	0.63

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<b>TABLE 6.9</b>		
<b>METHODS AND PROCEDURES FOR CONDUCTING EMISSIONS TESTS FOR STACK SYSTEMS</b>		
<b>For each stack system for which you use Tier 3b method to calculate annual emissions...</b>	<b>You should...</b>	<b>Using the method cited below or equivalent...</b>
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.

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<b>TABLE 6.10</b> <b>MAXIMUM FIELD DETECTION LIMITS (FDL) APPLICABLE TO FLUORINATED COMPOUNDS (FC) CONCENTRATION</b> <b>MEASUREMENTS FOR STACK SYSTEMS</b>	
<b>Fluorinated GHG Analyte</b>	<b>Maximum Field detection limit (ppbv*)</b>
CF <sub>4</sub>	20
C <sub>2</sub> F <sub>6</sub>	20
C <sub>3</sub> F <sub>8</sub>	20
C <sub>4</sub> F <sub>6</sub>	20
c-C <sub>4</sub> F <sub>8</sub>	20
C <sub>5</sub> F <sub>8</sub>	20
CHF <sub>3</sub>	20
CH <sub>2</sub> F <sub>2</sub>	40
CH <sub>3</sub> F	40
NF <sub>3</sub>	20
SF <sub>6</sub>	4
Other fully fluorinated GHGs	20
Other fluorinated GHGs	40
* ppbv = parts per billion by volume	

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## 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 6.12). Figure 6.4 provides guidance for deciding when a particular emissions control technology may be suitable to abate fluorinated compounds (FCs) and N<sub>2</sub>O 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 gas” 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<sub>3</sub>- or F<sub>2</sub>-based remote plasma clean (RPC) applications (step [1] in Figure 6.4). Indeed, these processes lead to the formation of significant amounts of molecular fluorine (F<sub>2</sub>) originating from the conversion of NF<sub>3</sub> into F<sub>2</sub> or the limited utilization efficiency of F<sub>2</sub> (when the latter is used as a cleaning precursor), and, when the exhaust gas contain large amounts of F<sub>2</sub> AND when hydrocarbon-fuel-based combustion emissions control technology is used, direct reaction with hydrocarbon fuel and F<sub>2</sub> to form CF<sub>4</sub> can occur. Unless the original equipment manufacturer (OEM) or the electronic devices manufacturer can certify that the rate of conversion from F<sub>2</sub> to CF<sub>4</sub> or from NF<sub>3</sub> to CF<sub>4</sub> is <0.1% on a mass basis, a default value of AB<sub>NF<sub>3</sub>,CF<sub>4</sub></sub> = 0.093 or AB<sub>F<sub>2</sub>,CF<sub>4</sub></sub> = 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<sub>4</sub> produced within and emitted from the emissions control device (step [2] in Figure 6.4).

Second, inventory compilers should consider 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 6.11, 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 6.11. Note that the absence of an ‘X’ in Table 6.11 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). Because new emissions control technologies could emerge, a ‘T’ in last row of Table 6.11 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 under representative gas flow conditions, defaults (or site-specific) DREs can be achieved using an industry-accepted measurement methodology that accounts for dilution.<sup>4,5,6</sup>

Third, inventory compilers should consider whether site-specific emissions control technologies are certified by the OEM(s) to meet the default DRE values indicated in Table 6.12 (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<sub>2</sub>O 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<sub>2</sub> 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 6.8 (step [5] of Figure 6.4), the corresponding DRE value should be set to zero (0%), or the reporting facility may set the DRE value using site-specific DREs that should have been measured on-site or certified by the OEM using an industry-accepted measurement methodology and for the site-specific worst case scenarios as previously described. The same procedure should be followed in the case the reporting facility wishes to claim a DRE value higher than the default DRE values of Table 6.12 (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% of the installed emissions control equipment population is tested annually for a representative sample of process applications. To use OEM-specific DREs, the test conditions and range of input process gas and total gas for which the DRE is applicable must be stated.

Fourth, 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 pump purge, 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

<sup>4</sup> 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](https://www.epa.gov/sites/production/files/2016-02/documents/dre_protocol.pdf)

<sup>5</sup> 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](http://www.lexissecuritiesmosaic.com/gateway/FedReg/document_4825beng.pdf)

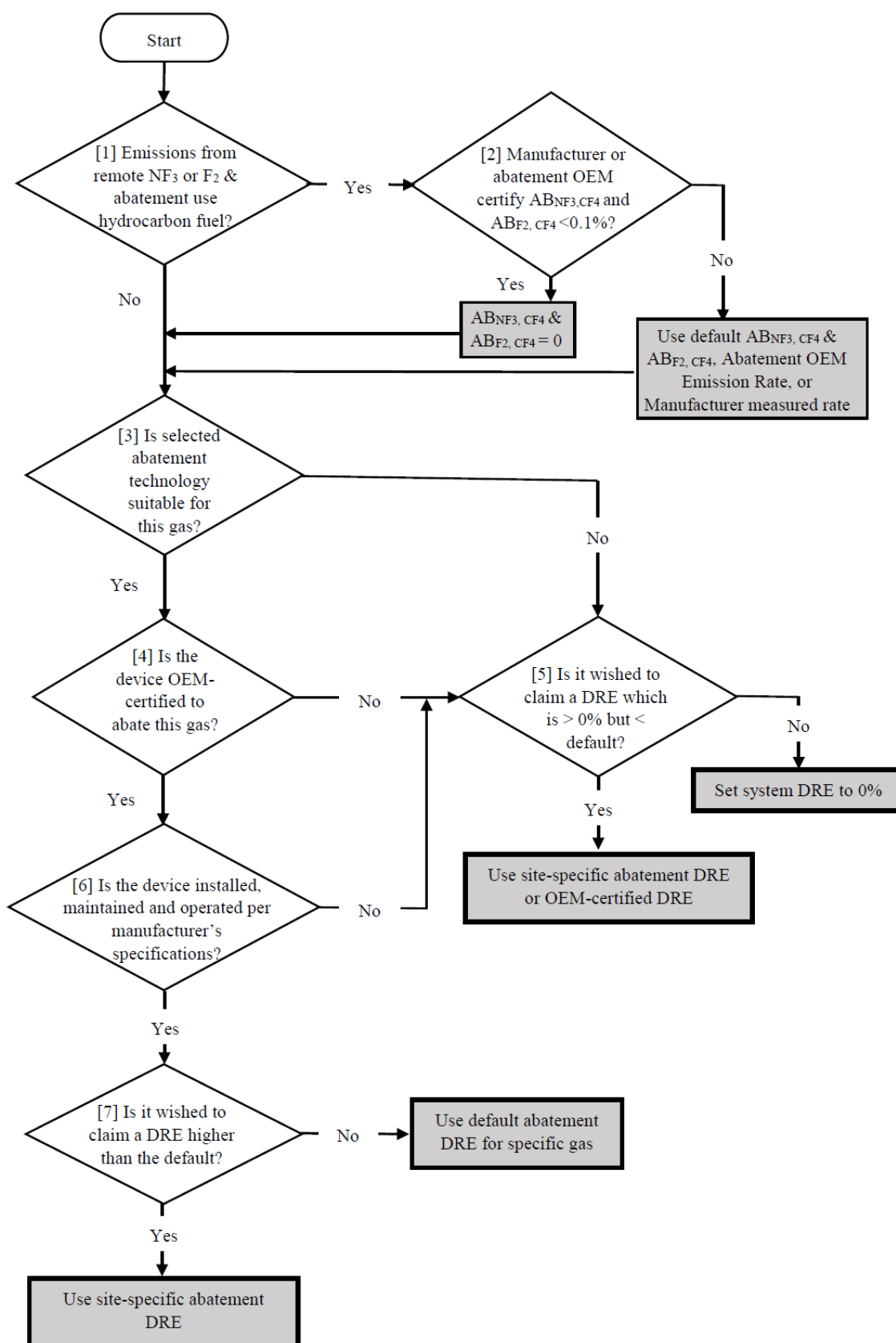
<sup>6</sup> JEITA Guideline for F-GHG Characterization and Management. Japan Electronics and Information Technologies Industries Association (2011). [http://semicon.jeita.or.jp/committee/docs/F-GHG\\_guideline\\_20110520\\_en.pdf](http://semicon.jeita.or.jp/committee/docs/F-GHG_guideline_20110520_en.pdf)

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suppliers' maximum flow specifications requires that all gases, including post-process-chamber purges, are taken into account. Also note that some vacuum pump 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%. Calibration should be performed every time a vacuum pump is serviced or exchanged.

TABLE 6.11 (NEW)																	
EMISSIONS CONTROL EQUIPMENT SUITABILITY TABLE FOR DESTRUCTION REMOVAL EFFICIENCY (DRE) OF PROCESS GHG EMISSIONS																	
Emissions Control Equipment Technology	Process GHG Emission																
	CF <sub>4</sub>	C <sub>2</sub> F <sub>4</sub>	C <sub>2</sub> F <sub>6</sub>	C <sub>3</sub> F <sub>6</sub> O	C <sub>3</sub> F <sub>8</sub>	C <sub>4</sub> F <sub>6</sub>	C <sub>4</sub> F <sub>6</sub> O	c-C <sub>4</sub> F <sub>8</sub>	C <sub>4</sub> F <sub>8</sub> O	C <sub>3</sub> F <sub>8</sub>	CHF <sub>3</sub>	CH <sub>2</sub> F <sub>2</sub>	CH <sub>3</sub> F	C <sub>2</sub> HF <sub>5</sub>	NF <sub>3</sub>	SF <sub>6</sub>	N <sub>2</sub> O
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		
Plasma	X	X	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	X	X
New technology	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
<p>‘X’ indicates that the technology is potentially suitable to use the default DRE for the particular gas.</p> <p>“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 representative gas flow conditions, defaults (or site-specific) DREs can be achieved using an industry-accepted measurement methodology that accounts for dilution.</p> <p><u>Emissions Control Equipment technology definitions:</u></p> <p>Cartridge – Any form of dry-bed passive gas treatment, either heated or ambient-temperature. The active media is consumed by reaction with the target gas.</p> <p>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.</p> <p>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.</p> <p>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, hydrogen and/or oxygen as chemical reagents.</p> <p>Combustion – This includes all configurations of fuel combustion and reaction zone configuration, water- or air-cooled, and dry or wet post-scrubbing.</p> <p>New Technology – This is to account for the possibility of new emissions control technologies emerging that are not included in the categories above.</p>																	

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





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**TABLE 6.12 (NEW)**  
**TIER 2 DEFAULT DRE PARAMETERS FOR ELECTRONICS INDUSTRY PROCESS GAS EMISSIONS REDUCTION TECHNOLOGIES**

Process Gas	CF <sub>4</sub>	C <sub>2</sub> F <sub>4</sub>	C <sub>2</sub> F <sub>6</sub>	C <sub>3</sub> F <sub>6</sub> O (b)	C <sub>3</sub> F <sub>8</sub>	C <sub>4</sub> F <sub>6</sub>	C <sub>4</sub> F <sub>6</sub> O (b)	c-C <sub>4</sub> F <sub>8</sub>	C <sub>4</sub> F <sub>8</sub> O (b)	C <sub>5</sub> F <sub>8</sub> (a)	CHF <sub>3</sub>	CH <sub>2</sub> F <sub>2</sub>	CH <sub>3</sub> F	C <sub>2</sub> HF <sub>5</sub> (a)	NF <sub>3</sub>	SF <sub>6</sub>	N <sub>2</sub> O
<b>DRE</b>	89	96	95	99	99	98	98	98	98	98	98	98	98	95	95	95	60

Source: 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<sub>4</sub>F<sub>8</sub> is used as the analogue for C<sub>5</sub>F<sub>8</sub>, C<sub>4</sub>F<sub>8</sub>O as it is cyclic and for C<sub>4</sub>F<sub>6</sub>O as it has similar composition to C<sub>4</sub>F<sub>8</sub>, 4-carbon. C<sub>2</sub>F<sub>6</sub> is used as the analogue for C<sub>2</sub>HF<sub>5</sub> and C<sub>2</sub>H<sub>5</sub>F as it is linear 2-carbon. C<sub>3</sub>F<sub>8</sub> is used as the analogue for C<sub>3</sub>F<sub>6</sub>O as it has similar composition to C<sub>3</sub>F<sub>8</sub> and is 3-carbon. For future compounds, apply C<sub>4</sub>F<sub>8</sub> for any cyclic compound, and follow linear analogue relative to C for those remaining.

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## 1824 6.2.2.2 FLUORINATED LIQUIDS

**TABLE 6.13 (NEW)**  
**TIER 1 DEFAULT EMISSION FACTORS FOR FLUORINATED LIQUIDS**

Representative Fluorinated Liquids	Electronics Industry Sector		
	Semiconductor manufacturing (kg/m <sup>2</sup> )	Semiconductor “burn-in” testing (kg/kpcs)	Display (kg/m <sup>2</sup> )
HFE-449sl	0.06	1 x 10 <sup>-4</sup>	0.00002
C <sub>6</sub> F <sub>14</sub>	0.07	3 x 10 <sup>-5</sup>	0.00004
PFPME	0.04	1 x 10 <sup>-5</sup>	0.00004

Note:

1. The default emission factors for semiconductor manufacturing 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<sub>6</sub>F<sub>14</sub> is used to represent fully fluorinated liquids manufactured by 3M™; and PFPME is used to represent fully fluorinated liquids manufactured by Solvay™.

2. Default emission factors for semiconductor “burn-in” testing 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 fluorinated liquid Tier 1 default for PV and thus the only solution for estimating emissions of fluorinated liquids from PV is the Tier 2 method.

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## 1826 6.2.3 Choice of activity data

1827 Activity data for the electronics industry consists of data on gas sales/purchases and/or production figures (surface  
1828 area of substrate used during the production of electronic devices, e.g. silicon, glass). For the more data-intensive  
1829 Tier 2 methods, gas consumption data at the company or plant-level are necessary. For the Tier 1 methods,  
1830 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 Watch (WFW) database, published quarterly by Semiconductor Equipment & Materials International (SEMI).<sup>7</sup> 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 and much more. Other databases are available e.g., IC Insights, Gartner and VLSI.<sup>8,9,10</sup> 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.<sup>11</sup>

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. Semiconductor and display manufacturing plants are not operated at design capacities for sustained periods, such as a full year. Instead, the production 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. This should be used consistently for a time series of estimates. For display manufacturing, 2016 fab capacity utilisation ranged between 76 and 91 percent<sup>12</sup>. 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 for  $C_u$  (see Equation 6.1) to use.

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). Recent surveys indicate that PV manufacturers no longer use thin film technology and, thus, do not process greenhouse gases. If thin film is not used then  $F_{PV}$  is 0,

## 6.2.4 Completeness

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

- **Tier 1 estimates:** The Tier 1 method is incomplete in the sense that not all gases are necessarily included in the emissions estimates (see Table 6.2 for each sub-sector) and does not take into account emissions control equipment. Further, as mentioned earlier, the Tier 1 method is the least accurate method and should be used only in cases where facility-specific data are not available. Because most facilities emit gases and by-products other than those accounted for in the Tier 1 method and may use emissions control equipment, using a Tier 2 or Tier 3 method is suggested.
- **Other greenhouse by-products:** A number of greenhouse by-products are generated as a result of the reaction of input gases during electronic devices manufacturing. While the Tier 2a, 2b, and 2c emission factors include by-product emissions factors ( $B_{k,i}$ ) to the extent that the formation of the by-products was detected as part of the experimental measurement of emissions for any particular recipe, other greenhouse by-products may be formed by alternate recipes, and may not be accounted for as part of default Tier 2a, 2b, or 2c emission factors. In particular, this may be the case for new gases and processes that have not been extensively characterized, in which instance it is suggested to adopt a partial Tier 3a approach, using Tier 2 default emission factors for conventional gases and processes and using measured emission factors for processes that use new gases or that emit greenhouse gas by-products.
- **New chemicals or new processes:** In the case where a new input fluorinated chemical or a new process is used for which no default emission factor has been established, the 2019 Refinement includes a provision for facilities to estimate emissions from the use of the new input gas or process using a Tier 2 method and assume

<sup>7</sup> 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.

<sup>8</sup> <http://www.icinsights.com/services/global-wafer-capacity/>

<sup>9</sup> <https://www.gartner.com>

<sup>10</sup> <https://www.vlsiresearch.com/>

<sup>11</sup> <https://technology.ihs.com/>

<sup>12</sup> <https://electroiq.com/2016/11/display-panel-makers-increase-fab-utilization-rate-to-90-in-q4-2016/>.

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a default emission factor of  $(1-U) = 0.8$ , with by-product emission factors of 0.15 for  $\text{CF}_4$  and 0.05 for  $\text{C}_2\text{F}_6$ . However, this provision could lead to incomplete and inaccurate results if the use of the new chemical leads to the formation of FC by-products other than  $\text{CF}_4$  and  $\text{C}_2\text{F}_6$  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% of the facility's fluorinated GHG consumption by mass. In any case, completeness will require inventory compilers to periodically review whether new chemicals or new process technologies have been implemented in production conditions, and *good practice* for this industry is to incorporate a mechanism that accounts for reporting new chemistries or process technologies that may affect emissions estimates, and for periodically reporting newly measured emission factors to the IPCC emission factors database (EFDB) in a transparent manner through a process (still to be designed at the time of writing of this *2019 Refinement*) allowing protection of the underlying confidential nature of the information.

- **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 gas purchases in support of R&D and tool commissioning activities may be included as part of the consumption figures used for a particular facility, and that the Tier 2 default emission factors can be used for reporting emissions from such activities. In the case that no default values exist for a new gas or process type tested for R&D purposes or used for tool commissioning, a default utilization efficiency of  $(1-U) = 0.8$  and by-product emission factors of 0.15 for  $\text{CF}_4$  and 0.05  $\text{C}_2\text{F}_6$  can be used, so long as the consumption of the new gas does not exceed 1% of the facility's GHG consumption by mass. If the 1% threshold is exceeded, facilities should measure the emission factors for the new gas or process type and use a partial Tier 3a method to account for emissions resulting from R&D and tool commissioning activities.

## 6.2.5 Developing a consistent time series

Use of FCs and  $\text{N}_2\text{O}$  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 method, then the Tier 1 method using default emission parameters can be used retrospectively. It is *good practice* to use the Tier 1 factors from the *2006 IPCC Guidelines* for years through 2010, and to use the Tier 1 factors from the *2019 Refinement* for 2011 and following years. Both Tier 1 and Tier 2 could then be applied simultaneously for the years in which more data become available to provide a comparison or benchmark. This should be done according to the guidance provided in Volume 1, Chapter 5.

In order to ensure a consistent emissions record over time, an inventory compiler should recalculate FC and  $\text{N}_2\text{O}$  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 or benchmark. 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

The uncertainty and accuracy of Tier 1 emission factors (EFs) could not be estimated due to the fact that the probabilities of distribution functions for the main Tier 1 factors are unknown. In particular, the uncertainty and accuracy of emission factor expressed as annual mass of emissions per square meters of substrate surface area ( $EF_i$ ) are unknown. It should also be noted that reliable estimates of annual production figures for any particular country may be difficult to obtain, and that Tier 1 emission factors only cover a subset of the types of FC gases or fluorinated liquids that any particular electronic devices manufacturing facility may emit (see Table 6.2). 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% confidence level, estimated for each emission factor of the Tier 2b, and 2c methods, are shown in Tables 6.14, and 6.15 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 granularity in the 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.

For fluorinated liquids, the uncertainty of the Tier 2 method will depend on the accuracy of the inventory method and can be evaluated by quantifying inventory losses (acquisitions not accounted for use in a particular piece of equipment). 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.

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 probabilities of distribution functions (PDFs) of the emission factors. Approaches to combine uncertainties include the propagation of error method and Monte Carlo simulations (see *2019 Refinement, Volume 1, Chapter 3*). 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% 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 probability of distribution function (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

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1995 describe the probabilities of distribution functions of the variables. Then, suitable PDFs should be used to describe  
1996 the variations of activity data (e.g. fuel, input gas consumption, emissions control equipment efficiency – see  
1997 Section 6.3.2) and such PDFs should be combined with those of the emission factors to estimate the uncertainty  
1998 of the total emissions calculations. Finally, a pseudo-random number generator (PRNG) should be used to generate  
1999 random inputs according to each probability of distribution function in the model, and the Monte Carlo engine will  
2000 calculate emissions for each combination of inputs. It is suggested that a minimum of 10,000 trials be used to  
2001 calculate total emissions in order to obtain a reasonable precision in describing the probability of distribution  
2002 function of total emissions.

2003 The accuracy of Tier 2 emission factors could not be estimated. This is in part because no information is publicly-  
2004 available to compare the results of Tier 2a, Tier 2b, or Tier 2c emissions estimates with the results of Tier 3a or  
2005 Tier 3b estimates. However, it should be noted that comparing Tier 2 and Tier 3a (bottom-up) estimates with Tier  
2006 3b (top-down) estimates for representative facilities could help assess the accuracy of the various methods. This  
2007 is because comparing Tier 2 (or preferably Tier 3a) estimates with Tier 3b estimates would help assess whether  
2008 biases can exist between top-down and bottom-up estimates. The Tier 2 and Tier 3a methods are deemed ‘bottom-  
2009 up’ approaches because they are based upon consumption at the tool level, while the Tier 3b method is considered  
2010 to be a ‘top-down’ approach as it is based on measuring stack-specific (end of pipe) emission factors. It should  
2011 also be noted that, when using the Tier 3b method, stack testing is used to develop facility specific emission factors.  
2012 In this case, because emission factors (stack-specific utilization efficiencies and by-product formation factors) can  
2013 be measured with a good degree of accuracy, the uncertainty of Tier 3b emissions estimates is mostly driven by  
2014 the uncertainty of activity data such as consumption, stack gas apportioning, and estimates of the overall emissions  
2015 control equipment efficiency. Please see Section 6.3.2 for further details regarding activity data uncertainty.

2016

<b>TABLE 6.14 (UPDATED)</b> <b>ESTIMATES OF RELATIVE UNCERTAINTIES (%) OF TIER 2B EMISSION FACTORS FOR SEMICONDUCTOR MANUFACTURING, 95 PERCENT CONFIDENCE INTERVALS.</b>																			
Process Gas	CF <sub>4</sub>	C <sub>2</sub> F <sub>6</sub>	C <sub>3</sub> F <sub>8</sub>	C <sub>3</sub> F <sub>8</sub> Remote	C <sub>4</sub> F <sub>6</sub>	c-C <sub>4</sub> F <sub>8</sub>	C <sub>4</sub> F <sub>8</sub> O	C <sub>5</sub> F <sub>8</sub>	CHF <sub>3</sub>	CH <sub>2</sub> F <sub>2</sub>	CH <sub>3</sub> F	C <sub>2</sub> HF <sub>5</sub>	NF <sub>3</sub> Remote	NF <sub>3</sub>	SF <sub>6</sub>	N <sub>2</sub> O TFD	N <sub>2</sub> O Other	COF <sub>2</sub>	F <sub>2</sub>
<b>≤200 mm wafer size</b>																			
(1-U <sub>i</sub> )	†	40	†	NA	200	†	†	†	100	160	†	100	200	150	†	NA	NA	NA	NA
B <sub>CF4</sub>	NA	120	†	NA	200	†	†	NA	80	140	NA	100	180	†	†	NA	NA	NA	NA
B <sub>C2F6</sub>	400	NA	NA	NA	400	†	†	†	200	120	†	140	NA	†	†	NA	NA	NA	NA
B <sub>C3F8</sub>	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B <sub>C5F8</sub>	†	NA	NA	NA	NA	†	NA	NA	†	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B <sub>CHF3</sub>	120	†	NA	NA	†	†	NA	†	NA	†	NA	NA	NA	NA	†	NA	NA	NA	NA
<b>300 mm wafer size</b>																			
(1-U <sub>i</sub> )	60	†	†	†	200	140	NA	180	120	200	140	NA	400	200	140	120	NA	NA	NA
B <sub>CF4</sub>	NA	†	†	NA	400	200	NA	160	200	200	200	NA	600	†	400	NA	NA	NA	NA
B <sub>C2F6</sub>	200	NA	†	NA	400	160	NA	200	400	200	200	NA	NA	400	200	NA	NA	NA	NA
B <sub>C3F8</sub>	NA	NA	NA	NA	NA	NA	NA	†	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B <sub>C4F6</sub>	†	NA	NA	NA	NA	†	NA	NA	†	NA	40	NA	NA	NA	NA	NA	NA	NA	NA
B <sub>C4F8</sub>	400	NA	NA	NA	†	NA	NA	NA	†	†	†	NA	NA	NA	NA	NA	NA	NA	NA
B <sub>CH3F</sub>	200	NA	†	NA	†	†	NA	NA	400	†	NA	NA	NA	†	†	NA	NA	NA	NA
B <sub>CH2F2</sub>	†	NA	NA	NA	†	†	NA	NA	†	NA	†	NA	NA	†	†	NA	NA	NA	NA
B <sub>CHF3</sub>	200	NA	†	NA	400	200	NA	400	NA	180	200	NA	NA	400	†	NA	NA	NA	NA
† Insufficient data was available to calculate uncertainty.																			

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TABLE 6.15 (UPDATED)																	
DEFAULT ESTIMATES OF RELATIVE UNCERTAINTIES (%) OF TIER 2C EMISSION FACTORS FOR SEMICONDUCTOR MANUFACTURING (≤200 MM), 95 PERCENT CONFIDENCE INTERVALS																	
Process Gas	CF <sub>4</sub>	C <sub>2</sub> F <sub>6</sub>	C <sub>3</sub> F <sub>8</sub>	C <sub>4</sub> F <sub>6</sub>	c-C <sub>4</sub> F <sub>8</sub>	C <sub>4</sub> F <sub>8</sub> O	C <sub>5</sub> F <sub>8</sub>	CHF <sub>3</sub>	CH <sub>2</sub> F <sub>2</sub>	CH <sub>3</sub> F	C <sub>2</sub> HF <sub>5</sub>	NF <sub>3</sub>	SF <sub>6</sub>	N <sub>2</sub> O TFD	N <sub>2</sub> O Other	COF <sub>2</sub>	F <sub>2</sub>
<b>Etching or Wafer Cleaning (EWC)</b>																	
(1-U <sub>i</sub> )	40	60	NA	200	140	NA	†	100	160	†	100	140	100	NA	NA	NA	NA
B <sub>CF4</sub>	NA	180	NA	200	200	NA	NA	80	140	NA	100	†	†	NA	NA	NA	NA
B <sub>C2F6</sub>	400	NA	NA	400	400	NA	†	200	120	†	140	†	†	NA	NA	NA	NA
B <sub>C5F8</sub>	†	NA	NA	NA	†	NA	NA	†	NA	NA	NA	NA	NA	NA	NA	NA	NA
B <sub>CHF3</sub>	120	†	NA	†	†	NA	†	NA	†	NA	NA	NA	†	NA	NA	NA	NA
<b>Remote Plasma Cleaning (RPC)</b>																	
(1-U <sub>i</sub> )	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	200	NA	NA	NA	NA	NA
B <sub>CF4</sub>	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	180	NA	NA	NA	NA	NA
<b>In-situ Plasma Cleaning (IPC)</b>																	
(1-U <sub>i</sub> )	†	40	†	NA	†	†	NA	NA	NA	NA	NA	180	NA	NA	NA	NA	NA
B <sub>CF4</sub>	NA	120	†	NA	†	†	NA	NA	NA	NA	NA	†	NA	NA	NA	NA	NA
B <sub>C2F6</sub>	NA	NA	NA	NA	NA	†	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
<b>Thin Film Deposition (TFD)</b>																	
(1-U <sub>i</sub> )	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	†	NA	NA	NA
<b>Other</b>																	
(1-U <sub>i</sub> )	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	†	NA	NA
† Insufficient data was available to calculate uncertainty.																	

2021

<b>TABLE 6.15 (UPDATED) (CONTINUED)</b> <b>DEFAULT ESTIMATES OF RELATIVE UNCERTAINTIES (%) OF TIER 2C EMISSION FACTORS FOR SEMICONDUCTOR MANUFACTURING (300 MM), 95 PERCENT</b> <b>CONFIDENCE INTERVALS</b>															
Process Gas	CF <sub>4</sub>	C <sub>2</sub> F <sub>6</sub>	C <sub>3</sub> F <sub>8</sub>	C <sub>4</sub> F <sub>6</sub>	c-C <sub>4</sub> F <sub>8</sub>	C <sub>5</sub> F <sub>8</sub>	CHF <sub>3</sub>	CH <sub>2</sub> F <sub>2</sub>	CH <sub>3</sub> F	NF <sub>3</sub>	SF <sub>6</sub>	N <sub>2</sub> O TFD	N <sub>2</sub> O Other	COF <sub>2</sub>	F <sub>2</sub>
<b>Etching and Wafer Cleaning (EWC)</b>															
(1-U <sub>i</sub> )	60	†	†	200	140	180	120	200	140	180	140	NA	NA	NM	NM
B <sub>CF4</sub>	NA	†	†	400	200	160	200	200	200	200	400	NA	NA	NM	NM
B <sub>C2F6</sub>	200	NA	†	400	160	200	400	200	200	200	200	NA	NA	NM	NM
B <sub>C3F8</sub>	NA	NA	NA	NA	NA	†	NA	NA	NA	NA	NA	NA	NA	NA	NA
B <sub>C4F6</sub>	†	NA	NA	NA	†	NA	†	NA	40	NA	NA	NA	NA	NA	NA
B <sub>C4F8</sub>	400	NA	NA	†	NA	NA	†	†	†	NA	NA	NA	NA	NA	NA
B <sub>CH3F</sub>	200	NA	†	†	†	NA	400	†	NA	†	†	NA	NA	NA	NA
B <sub>CH2F2</sub>	†	NA	NA	†	†	NA	†	NA	†	†	†	NA	NA	NA	NA
B <sub>CHF3</sub>	200	NA	†	400	200	400	NA	180	200	200	†	NA	NA	NA	NA
<b>Remote Plasma Cleaning (RPC)</b>															
(1-U <sub>i</sub> )	NA	NA	†	NA	NA	NA	NA	NA	NA	400	NA	NA	NA	NA	NA
B <sub>CF4</sub>	NA	NA	NA	NA	NA	NA	NA	NA	NA	600	NA	NA	NA	NA	NA
<b>In-situ Plasma Cleaning (IPC)</b>															
(1-U <sub>i</sub> )	NA	NA	NA	NA	NA	NA	NA	NA	NA	100	NA	NA	NA	NA	NA
B <sub>CF4</sub>	NA	NA	NA	NA	NA	NA	NA	NA	NA	†	NA	NA	NA	NA	NA
<b>In-situ Thermal Cleaning (ITC)</b>															
(1-U <sub>i</sub> )	NA	NA	NA	NA	NA	NA	NA	NA	NA	†	NA	NA	NA	NA	NA
B <sub>CF4</sub>	NA	NA	NA	NA	NA	NA	NA	NA	NA	†	NA	NA	NA	NA	NA
<b>TFD</b>															
(1-U <sub>i</sub> )	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	120	NA	NA	NA
<b>Other</b>															
(1-U <sub>i</sub> )	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	†	NA	NA
† Insufficient data was available to calculate uncertainty.															

2022



## 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 subsectors (e.g. memory vs. logic 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 uncertainty and accuracy of Tier 1 emissions estimates could not be determined, and the Tier 1 method should only be used when 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). It should also be noted that, when completing Tier 2a or Tier 2b estimates, using default gamma values ( $\gamma_i$  and  $\gamma_k$ ) to estimate the ratio of the uncontrolled emissions of input gases 'i' or by-products 'k' from thin film deposition tools to the uncontrolled emissions 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 6.16). 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.

To minimize apportioning uncertainty and increase accuracy, it is *good practice* where feasible 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.

Finally, activity data related to the effective use of emissions control systems must 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.

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.

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TABLE 6.16 (NEW) TIER 2A & 2B METHODS – ESTIMATES OF RELATIVE UNCERTAINTIES (%) FOR $\gamma_i$ AND $\gamma_k$ (semiconductor), 95 PERCENT CONFIDENCE INTERVALS										
Process Gas	CF <sub>4</sub> IPC/EWC	CF <sub>4</sub> RPC/EWC	CF <sub>4</sub> (IPC+ITC)/EWC	C <sub>2</sub> F <sub>6</sub> IPC/EWC	C <sub>3</sub> F <sub>8</sub> RPC/EWC*	c-C <sub>4</sub> F <sub>8</sub> IPC/EWC	NF <sub>3</sub> IPC/EWC	NF <sub>3</sub> (IPC+ITC)/EWC	SF <sub>6</sub> IPC/EWC	N <sub>2</sub> O TFD/Other
$\gamma_i$ ( $\leq 200$ mm wafer size)	240	NA	NA	260	NA	200	180	NA	340	160
$\gamma_k$ ( $\leq 200$ mm wafer size)	220	NA	NA	340	NA	NA	NA	NA	NA	NA
$\gamma_i$ (300 mm wafer size)	NA	NA	NA	NA	320	NA	NA	280	NA	400
$\gamma_k$ (300 mm wafer size)	NA	100	280	NA	NA	NA	NA	NA	NA	NA
* Value estimated by analogy.										

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## 2069 6.4 QUALITY ASSURANCE / QUALITY CONTROL 2070 (QA/QC), REPORTING AND 2071 DOCUMENTATION

### 2072 6.4.1 Quality Assurance / Quality Control (QA/QC)

2073 It is *good practice* to conduct quality control checks as outlined in Volume 1, Chapter 6 of the *2019 Refinement*,  
2074 and an expert review of the emissions estimates. Additional quality control checks as outlined in Volume 1 and  
2075 quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine  
2076 emissions from this source category. Inventory compilers are encouraged to use higher tier QA/QC for *key*  
2077 *categories* as identified in Volume 1, Chapter 4.

2078 Additional general guidance for higher tier QA/QC procedures is also included in Volume 1, Chapter 6 of the *2019*  
2079 *Refinement*. Due to the highly competitive nature of the electronics industry, provisions for handling confidential  
2080 business information should be incorporated into the verification process. Methods used should be documented,  
2081 and a periodic audit of the measurement and calculation of data should be considered. A QA audit of the processes  
2082 and procedures should also be considered.

### 2083 6.4.2 Reporting and documentation

2084 Care should be taken not to include emissions of HFCs used as ODS substitutes with those used in semiconductor  
2085 manufacturing. It is *good practice* to document and archive all information required to produce facility level and  
2086 national emissions inventory estimates as outlined in Volume 1, Section 6.11 of the *2019 Refinement*. It is not  
2087 practical to include all documentation in the national inventory report. However, the inventory should include  
2088 summaries of methods used and references to source data such that the reported emissions estimates are transparent  
2089 and steps in their calculation may be retraced.

2090 Efforts to increase transparency should take into account the protection of confidential business information related  
2091 to specific gas use. Country-level aggregation of gas-specific emissions data should protect this information in  
2092 countries with three or more manufacturers. Table 6.17 (Information Necessary for Full Transparency of Estimates  
2093 of Emissions from Electronics Manufacturing), shows the supporting information necessary for full transparency  
2094 in reported emissions estimates.

2095 *Good practice* for Tier 3a and 3b is to document the development of company-specific emission factors, and to  
2096 explain the deviation from the generic default values. Given confidentiality concerns, inventory compilers may  
2097 wish to aggregate this information across manufacturers. In cases where manufacturers in a country have reported

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2098 different emission or conversion factors for a given fluorinated compound (FC) or N<sub>2</sub>O and for specific recipes or  
 2099 families of similar recipes, inventory compilers may provide the range of factors reported and used.  
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<b>TABLE 6.17 (NEW)</b> <b>INFORMATION NECESSARY FOR FULL TRANSPARENCY OF ESTIMATES OF EMISSIONS FROM ELECTRONICS MANUFACTURING</b>							
<b>Data</b>	<b>Tier 1</b>	<b>Tier 2 (Fluorinated liquids)</b>	<b>Tier 2a</b>	<b>Tier 2b</b>	<b>Tier 2c</b>	<b>Tier 3a</b>	<b>Tier 3b</b>
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 CVD chambers running carbon containing films to total number of CVD chambers.			X	X	X	X	
Number of EWC and TFD tools equipped suitable emissions control technologies.			X	X	X	X	X
Total number 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

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<b>TABLE 6.17 (NEW) (CONTINUED)</b> <b>INFORMATION NECESSARY FOR FULL TRANSPARENCY OF ESTIMATES OF EMISSIONS FROM ELECTRONICS MANUFACTURING</b>							
<b>Data</b>	<b>Tier 1</b>	<b>Tier 2 (Fluorinated liquids)</b>	<b>Tier 2a</b>	<b>Tier 2b</b>	<b>Tier 2c</b>	<b>Tier 3a</b>	<b>Tier 3b</b>
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 <sub>4</sub> 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
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
Preliminary estimates of stack emissions of input gases and by-products.							X
Fraction of total facility emissions included in the tested stacks.							X
Flow rates of the stack systems							X

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## References

### *References newly cited in the 2019 Refinement*

- Beu, L. (2011) ISMI Analysis of the Impact of Final Mandatory Reporting Rule Subpart I on U.S. Semiconductor Facilities, Technology Transfer #11015139A-TR International SEMATECH Manufacturing Initiative. URL <http://www.semtech.org/docubase/document/5139aeng.pdf>
- Beu, L. & Haslam, M. (2011) ISMI/SIA Alternative to Recipe-Specific Testing, URL <https://www.regulations.gov/document?D=EPA-HQ-OAR-2011-0028-0061>
- Beu, L. & Haslam, M. (2011) ISMI/SIA Alternative to Recipe-Specific-Testing (Updated document), URL <https://www.regulations.gov/document?D=EPA-HQ-OAR-2011-0028-0086>
- Cigal, J.-C., Lee, S. & Stockman, Paul. (2016) On-site fluorine chamber cleaning for semiconductor thin-film processes: shorter cycle times, lower greenhouse gas emissions, and lower power requirements. *27th Annual SEMI Advanced Semiconductor Manufacturing Conference, ASMC 2016*. Art. # 7491126: 201-205.
- Chen, L.T. & Hu, A.H. (2012) Voluntary GHG reduction of industrial sectors in Taiwan. *Chemosphere* **88** (9): 1074-82.
- Cheng, D., Hsu, J.-N. & Lu, J. (2017) F-gas and N<sub>2</sub>O emission factor study in optoelectronics and semiconductor industries. *IHTESH conference*.
- Cheng, D. & Lu, J. (2018) FCs Emission Factor and Next Steps Reduction emission for Taiwan's Industry. *SESHA/SIA ANNUAL SYMPOSIUM*
- Cheng, J.-H., Bartos, S.C., Lee, W.M., Li, S.-N. & Lu, J. (2013) SF<sub>6</sub> usage and emission trends in the TFT-LCD industry. *International Journal of Greenhouse Gas Control* **17**: 106–110.
- Choi, S., Park, D.-W. & Watanabe, T. (2012) Thermal plasma decomposition of fluorinated greenhouse gases. *Nuclear Engineering and Technology*, **44**(1), 21-32.
- Choi, S., Hong, S.H., Lee, H.S. & Watanabe, T. (2012) A comparative study of air and nitrogen thermal plasmas for PFCs decomposition. *Chem. Eng. J.*, 185-186, 193—200.
- De Blasi, M. & Weissinger, E. (2016) Washington State's New GHG Regulations: a case study for the future of GHG regulations for the high tech industry. *SESHA 2016 Symposium*
- Denko, S. (2011) SDK to Produce Eco-Friendly High-Purity COF<sub>2</sub> Gas for LCD Panels. URL <http://www.sdk.co.jp/english/news/2011/12415.html>
- Derbyshire, K. (2016) More than just carbon dioxide. URL <http://semiengineering.com/more-than-just-carbon-dioxide/>
- Doe, P. (2014) Next-generation sustainability gets more challenging. URL <http://semiengineering.com/next-generation-sustainability-gets-more-challenging/>
- Ecosian. (2012) How to construct energy / GHG reduction database in semiconductor, display, electric & electronic industries. *Semi-annual ETSAP meeting Oakwood Premier Coex Center*, 159 Samseong-Dong, Gangnam-gu, Seoul, Republic of Korea
- Erm West & Intel. (2011) FAB 32 General Scrubber End of Pipe (EOP) GHG Assessment Study. URL <https://www.regulations.gov/document?D=EPA-HQ-OAR-2011-0028-0042>
- EU Regulation. (2014) No 517 - Fluorinated greenhouse gases.
- European Equipment and Material 450 mm Initiative. (2013) The Move to the next silicon wafer size: a white paper from the European Equipment and Materials 450mm Initiative (EEMI450). URL [http://www.eemi450.org/White\\_paper\\_EEMI450\\_Final.pdf](http://www.eemi450.org/White_paper_EEMI450_Final.pdf)
- Fang, X., Hu, X., Janssens-Maenhout, G., Wu, J., Han, J., Su, S., Zhang, J. & Hu, J. (2014) Sulfur hexafluoride (SF<sub>6</sub>) emission estimates for China: An inventory for 1990-2010 and a projection to 2020. *Environmental Science and Technology*, **47**(8): 3848-55.
- Frankwicz, P.S., Gardner, L. & Moutinho, T. (2012) Reduction of greenhouse gas emissions by metal interconnect etch process optimization. *ECS Transactions*, **41**(34): 1-7.
- Fthenakis, V., Clark, D. O., Moalem, M., Chandler, P., Ridgeway, R.G., Hulbert, F.E., Cooper, D.B. & Maroulis, P.J. (2010) Life-cycle nitrogen trifluoride emissions from photovoltaics. *Environmental Science and Technology*, **44**(22): 8750-57.

- 2157 Gaines, J. (2016) Alternative heat transfer fluids reduce greenhouse gas emissions for the semiconductor industry.  
2158 URL [https://www.lesker.com/newweb/blog/post.cfm/alternative-heat-transfer-fluids-reduce-greenhouse-gas-](https://www.lesker.com/newweb/blog/post.cfm/alternative-heat-transfer-fluids-reduce-greenhouse-gas-emissions-for-the-semiconductor-industry)  
2159 [emissions-for-the-semiconductor-industry](https://www.lesker.com/newweb/blog/post.cfm/alternative-heat-transfer-fluids-reduce-greenhouse-gas-emissions-for-the-semiconductor-industry)
- 2160 Gilliland, T.M. & Laush, C. (2011) Developing a fluorinated greenhouse gas stack testing method using FTIR.  
2161 *SESHA 2011 Symposium*.
- 2162 Grand View Research. (2015) Nitrogen trifluoride (NF3) & fluorine gas (F2) market analysis by application and  
2163 segment forecasts to 2020. URL <http://www.grandviewresearch.com/press-release/global-nf3-and-f2-market>.
- 2164 G450C. (2014) Update to the 450mm equipment performance metrics (v7.0). URL  
2165 [http://www.g450c.org/G450C\\_EPM\\_Sub\\_10nm\\_v7\\_0\\_July\\_2014.pdf](http://www.g450c.org/G450C_EPM_Sub_10nm_v7_0_July_2014.pdf)
- 2166 Higgs, T. (2016) Reducing GHG emissions from heat transfer fluids. *SESHA 2016 Symposium*
- 2167 Hur, M., Lee, J.O., Lee, J.Y., Kang, W.S. & Song, Y.-H. (2016) Effects of pressure and electrode length on the  
2168 abatement of N2O and CF4 in a low-pressure plasma reactor. *Plasma Chemistry and Plasma Processing*, **36**(6):  
2169 1589-1601.
- 2170 IBM. (2012) 300mm Fab Stack Test Report, URL [https://www.regulations.gov/document?D=EPA-HQ-OAR-](https://www.regulations.gov/document?D=EPA-HQ-OAR-2011-0028-0043)  
2171 [2011-0028-0043](https://www.regulations.gov/document?D=EPA-HQ-OAR-2011-0028-0043)
- 2172 IBM. (2010) Semiconductor Engineering Models for Apportionment of Fluorinated Greenhouse Gases to Process  
2173 Categories, URL <https://www.regulations.gov/document?D=EPA-HQ-OAR-2011-0028-0075>
- 2174 Illuzzi, F. & Thewissen H. (2010) Perfluorocompounds emission reduction by the semiconductor industry. *Journal*  
2175 *of Integrative Environmental Sciences*, **7**(1), 201-10.
- 2176 Industrial Monitor & Control Corporation (IMACC). (2011) Test Report for the Enhanced FTIR Stack Sampling  
2177 of Greenhouse Gases (GHG): Alternative Study for 40CFR98 Subpart I Report Requirements, URL  
2178 <https://www.regulations.gov/document?D=EPA-HQ-OAR-2011-0028-0044>
- 2179 Intel. (2016) Abating greenhouse gases at Intel Corporation. Technology and Operations Management, URL  
2180 <https://rctom.hbs.org/submission/abating-greenhouse-gases-at-intel-corporation/>
- 2181 Intel. (2015) Intel Global Climate Change Policy Statement. URL  
2182 [http://www.intel.com/content/dam/www/public/us/en/documents/corporate-information/environment-](http://www.intel.com/content/dam/www/public/us/en/documents/corporate-information/environment-climate-change-policy-harper.pdf)  
2183 [climate-change-policy-harper.pdf](http://www.intel.com/content/dam/www/public/us/en/documents/corporate-information/environment-climate-change-policy-harper.pdf)
- 2184 International Energy Agency. (2004) Trends in Photovoltaic Applications: Survey report of selected IEA Countries  
2185 between 1992 – 2003. In: Photovoltaic Power Systems Programme (PVPS). Report IEA-PVPS T1-13:2004.  
2186 URL [http://www.iea-pvps.org/fileadmin/dam/public/report/statistics/tr\\_2003.pdf](http://www.iea-pvps.org/fileadmin/dam/public/report/statistics/tr_2003.pdf)
- 2187 International Sematech Manufacturing Initiative (ISMI). (2010) Comparison of Fourier Transform Infrared (FTIR)  
2188 and Quadrupole Mass Spectroscopy (QMS) Methods for Determining POU Abatement System Effluent Flow,  
2189 Technology Transfer #10095115A-ENG International SEMATECH Manufacturing Initiative, URL  
2190 <https://www.regulations.gov/document?D=EPA-HQ-OAR-2011-0028-0052>
- 2191 International Sematech Manufacturing Initiative (ISMI). (2014) Guideline for Characterization of Semiconductor  
2192 Process Equipment – Revision 3, SEMATECH Technology Transfer #06124825C-ENG, URL  
2193 <http://www.semtech.org/docubase/document/4825ceng.pdf>
- 2194 IPCC. (2007) IPCC Fourth Assessment Report. Direct Global Warming Potentials, Table 2.14, URL  
2195 [https://www.ipcc.ch/publications\\_and\\_data/ar4/wg1/en/ch2s2-10-2.html](https://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html)
- 2196 ISMI Stack Test Team. (2011) ISMI/SIA Stack Test Technical Presentation, URL  
2197 <https://www.regulations.gov/document?D=EPA-HQ-OAR-2011-0028-0060>
- 2198 JEITA. (2011) Guideline for F-GHG Characterization and Management, URL  
2199 [http://semicon.jeita.or.jp/committee/docs/F-GHG\\_guideline\\_20110520\\_en.pdf](http://semicon.jeita.or.jp/committee/docs/F-GHG_guideline_20110520_en.pdf)
- 2200 Kim, I.J., Moon, H.K., Lee, J.H., Lee, N.-E., Jung, J.W. & Cho C.H. (2012) Silicon nitride etch characteristics in  
2201 SF6/O2 and C3F6O/O2 plasmas and evaluation of their global warming effects. *Microelectronics Reliability*.  
2202 **52**(12), 2970-74.
- 2203 Kim, J., Li, P.J., Mühle, J., Fang, X., Manning, A.J., Arnold, T., Park, S., Park, M., Saito, T., Yokouchi, Y., Stohl,  
2204 A., Weiss, R.F. & Kim, K. (2013) Emissions of tetrafluoromethane (CF4) and hexafluoroethane (C2F6) from  
2205 East Asian Aluminum and Semiconductor Industries. *American Geophysical Union*, Fall Meeting 2013,  
2206 abstract #A32D-01

Final Draft

- 2207 Kim J., Li, P.J., Mühle, J., Ganesan, A. L., Krummel, P.B. & Kim, K.R. (2016) Quantifying aluminum and  
2208 semiconductor industry perfluorocarbon emissions from atmospheric measurements. *Geophys. Res. Lett.*, **41**:  
2209 4787–94.
- 2210 Kim, J.H., Cho C.H., Shin, D.H., Hong, Y.C. & Shin, Y.W. (2015) Abatement of fluorinated compounds using a  
2211 2.45GHz microwave plasma torch with a reverse vortex plasma reactor. *Journal of Hazardous Materials*, **294**:  
2212 41-46.
- 2213 Kim, K.Y., Moon, H.K., Lee, N.-E., Soo, H.O. (2015) Comparative study of global warming effects during silicon  
2214 nitride etching using C3F6O/O2 and C3F6/O2 gas mixtures. *Electronic Materials Letters*, **11**(1): 93–99.
- 2215 Ko D.G., Ko, S.J., Choi, E.K., Min, S.G., Oh, S.H., Jung, J., Kim, B.M. & Im, I.-T. (2014) Perfluorocarbon  
2216 destruction and removal efficiency: considering the byproducts and energy consumption of an abatement  
2217 system for microelectronics manufacturing. *IEEE Transactions on Semiconductor Manufacturing*, **27** (4),456-  
2218 61.
- 2219 Lim, M.S., Kim, S.C. & Chun, Y.N. (2011) Decomposition of PFC gas using a water jet plasma. *Journal of*  
2220 *Mechanical Science and Technology*, **25**(7): 1845-51
- 2221 Liu, X., Zhang, J., Zhang, R., Hou, H., Chen, S. & Zhang, Y. (2014) Photoreduction of nitrogen trifluoride with  
2222 controlled release of radicals. *Journal of Chemical Technology and Biotechnology*, **89**(3): 436-447.
- 2223 Maynes, A. (2014a) 450mm transition toward sustainability: facility and infrastructure requirements. URL  
2224 [http://electroi.com/blog/2014/06/450mm-transition-toward-sustainability-facility-and-infrastructure-](http://electroi.com/blog/2014/06/450mm-transition-toward-sustainability-facility-and-infrastructure-requirements/)  
2225 [requirements/](http://electroi.com/blog/2014/06/450mm-transition-toward-sustainability-facility-and-infrastructure-requirements/)
- 2226 Maynes, A. (2014b) Sustainability challenges in the 450mm technology node. URL  
2227 [http://www.semi.org/en/sites/semi.org/files/docs/04\\_Adrian\\_Maynes\\_F450C.pdf](http://www.semi.org/en/sites/semi.org/files/docs/04_Adrian_Maynes_F450C.pdf)
- 2228 McCoy, M. (2012) Fluorine-based compounds face-off over electronics market. *Chemical and Engineering News*,  
2229 **89** (48): 21-23.
- 2230 Mitchell, G., et al. (2013) Development of Green NF3™; lowering the cost and environmental impact of NF3  
2231 through the use of additives. URL [https://www.tn-sanso-giho.com/pdf/32/tncsgiho32\\_03.pdf](https://www.tn-sanso-giho.com/pdf/32/tncsgiho32_03.pdf)
- 2232 Mühle, J., Ganesan, A. L., Miller, B. R., Salameh, P. K., Harth, C. M., Grealley, B. R., Rigby, M., Porter, L. W.,  
2233 Steele, L. P., Trudinger, C. M., Krummel, P. B., O'Doherty, S., Fraser, P. J., Simmonds, P. G., Prinn, R. G. &  
2234 Weiss, R. F. (2010) Perfluorocarbons in the global atmosphere: tetrafluoromethane, hexafluoroethane, and  
2235 octafluoropropane. *Atmospheric Chemistry and Physics*, **10**(11), 5145-64.
- 2236 Neuber, A., Cayer, M. & Van Gompel, J. (2015a) Computer based monitoring of F-GHG emissions in  
2237 semiconductor fabs. *SESHA 2015 Symposium*.
- 2238 Neuber, A., Cayer, M., Crawford, S. & Herbert, A. (2015b) Trends in subfab energy consumption and emissions  
2239 control. URL [http://www.appliedmaterials.com/nanochip/nanochip-fab-solutions/july-2015/trends-in-subfab-](http://www.appliedmaterials.com/nanochip/nanochip-fab-solutions/july-2015/trends-in-subfab-energy-consumption-and-emissions-control)  
2240 [energy-consumption-and-emissions-control](http://www.appliedmaterials.com/nanochip/nanochip-fab-solutions/july-2015/trends-in-subfab-energy-consumption-and-emissions-control)
- 2241 Office of Sustainability, City of Austin. (2014) Industrial Process Advisory Group. URL  
2242 [https://austintexas.gov/sites/default/files/files/Sustainability/Climate/Industrial\\_TAG\\_Sept\\_17\\_update.pdf](https://austintexas.gov/sites/default/files/files/Sustainability/Climate/Industrial_TAG_Sept_17_update.pdf)
- 2243 Oh, C.H., Ko, S.J., Shin, D.K. & Jeong, Y.Y. (2012) Improving eco-efficiency via elimination of greenhouse gases  
2244 from semiconductor dry cleaning processes. *ASMC (Advanced Semiconductor Manufacturing Conference)*  
2245 *Proceedings*. Art. #6212907: 257-260.
- 2246 Ohkura, M. (2012) Fluorinated Compounds Emission Reduction Activity of WLICC (World LCD Industry  
2247 Cooperation Committee). *SID Symposium Digest of Technical Papers*, **43**(1): 838-41.
- 2248 Ottinger, D., Averyt, M. & Harris, D. (2015) US consumption and supplies of sulphur hexafluoride reported under  
2249 the greenhouse gas reporting program.. *Journal of Integrative Environmental Sciences*, **12**(5): 16.
- 2250 Plasma Air AG. (2016) Plasma scrubber. URL <https://plasmaair.de/en/plasma-scrubber/>
- 2251 Purohit, P. & Höglung-Isaksson, L. (2017) Global emissions of fluorinated greenhouse gases 2005-2050 with  
2252 abatement potentials and costs. *Atmos. Chem. Phys.*, **17**: 2795-2816.
- 2253 Quartz Corp. (2015) Will 450mm wafers ever become industry standard? URL  
2254 <http://www.thequartzcorp.com/en/blog/2015/08/17/will-450mm-wafers-ever-become-industry-standard/153>
- 2255 Raoux, S., Tanaka, T., Bhan, M., Ponnekanti, H., Seamons, M., Deacon, T., Xia, L.Q., Pham, F., Silveti, D.,  
2256 Cheung, D., Fairbairn, K., Jonhson, A., Pearce, R., and Langan, J.G. (1999) Remote microwave plasma source



- 2257 for cleaning CVD chambers - A technology for reducing global warming gas emissions. *Journal of Vacuum*  
2258 *Science & Technology B*, **17**(2), pp.477-85.
- 2259 Regulations.gov. (2011) Correction and Supplement to Comments at EPA Docket ID No. EPA-HQ-OAR-2010-  
2260 0964-0024.1. Comments of the Semiconductor Industry Association on EPA's Call for Information:  
2261 Information on Inputs to Emissions Equations Under The Mandatory Reporting of Greenhouse Gases Rule 75  
2262 FED. REG. 81365.
- 2263 Rigby, M., Prinn, R. G., O'Doherty, S., Miller, B. R., Ivy, D., Muhle, J., Harth, C. M., Salameh, P. K., Arnold, T.,  
2264 Weiss, R. F., Krummel, P. B., Steele, L. P., Fraser, P. J., Young, D. & Simmonds, P. G. (2014) Recent and  
2265 future trends in synthetic greenhouse gas radiative forcing. *Geophys. Res. Lett.*, **41** (7): 2623-2630.
- 2266 Sekiya, A. & Okamoto, S. (2011) Global warming evaluation of chamber cleaning gases by new indicators, CEWN  
2267 and CETN. *SESHA 2011 Symposium*
- 2268 Semiconductor Industry Association. (2011) Petition for Reconsideration and Request for Stay Pending  
2269 Reconsideration of Subpart I of the Final Rule for Mandatory Reporting of Greenhouse Gases, DOCKET NO.  
2270 EPA-HQ-OAR-2009-0927, URL <https://www.regulations.gov/document?D=EPA-HQ-OAR-2011-0028-0070>
- 2271 Semiconductor Industry Association. (2012a) Measured Gas Usage During Stack Testing, April 28, 2012, URL  
2272 <https://www.regulations.gov/document?D=EPA-HQ-OAR-2011-0028-0066>
- 2273 Semiconductor Industry Association. (2012b) Briefing Paper on Abatement Issues: Destruction Removal  
2274 Efficiency (DRE), Submitted as part of settlement documents for SIA v. EPA (D.C. Cir. No. 1024), URL  
2275 <https://www.regulations.gov/document?D=EPA-HQ-OAR-2011-0028-0045>
- 2276 Semiconductor Industry Association. (2015) Semiconductor industry concerns with inclusion of abatement  
2277 requirement in product environmental standards. URL  
2278 [https://www.semiconductors.org/clientuploads/directory/DocumentSIA/Environment/Abatement%20in%20p](https://www.semiconductors.org/clientuploads/directory/DocumentSIA/Environment/Abatement%20in%20product%20standards%20nov%202015.pdf)  
2279 [roduct%20standards%20nov%202015.pdf](https://www.semiconductors.org/clientuploads/directory/DocumentSIA/Environment/Abatement%20in%20product%20standards%20nov%202015.pdf)
- 2280 Solvay. (2012) Method of plasma etching and plasma chamber cleaning using F2 and COF2. US Patent application  
2281 number 20120214312. URL [http://appft1.uspto.gov/netacgi/nph-](http://appft1.uspto.gov/netacgi/nph-Parser?Sect1=PTO1&Sect2=HITOFF&d=PG01&p=1&u=/netahtml/PTO/srchnum.html&r=1&f=G&l=50&s1=20120214312.PG NR)  
2282 [Parser?Sect1=PTO1&Sect2=HITOFF&d=PG01&p=1&u=/netahtml/PTO/srchnum.html&r=1&f=G&l=50&s](http://appft1.uspto.gov/netacgi/nph-Parser?Sect1=PTO1&Sect2=HITOFF&d=PG01&p=1&u=/netahtml/PTO/srchnum.html&r=1&f=G&l=50&s1=20120214312.PG NR)  
2283 [1=20120214312.PG NR](http://appft1.uspto.gov/netacgi/nph-Parser?Sect1=PTO1&Sect2=HITOFF&d=PG01&p=1&u=/netahtml/PTO/srchnum.html&r=1&f=G&l=50&s1=20120214312.PG NR)
- 2284 Solvay. (2014) Sifren 46 - Cleaning gas for the use in plasma, ion beam or sputter etching in semiconductor devices  
2285 manufacturing. URL <https://www.solvay.com/en/markets-and-products/featured-products/sifren-46.html>
- 2286 Stockman, P. (2016) On-site generated fluorine: effective, safe, and reliable source of fluorine for electronics for  
2287 over 15 years. *Silicon Semiconductor*. **38**(2): 2-12
- 2288 Sung, L.Y. (2014) Locating sources of hazardous gas emissions using dual pollution rose plots and open path  
2289 Fourier transform infrared spectroscopy. *Journal of Hazardous Materials*, **265**: 30-40.
- 2290 Tajima, S., Hayashi, T., Ishikawa, K., Sekine, M. & Hori, M. (2013) Room-Temperature Si Etching in NO/F2  
2291 Gases and the Investigation of Surface Reaction Mechanisms. *J. Phys. Chem. C*. **117** (10): 5118-5125.
- 2292 Trudinger C.M., Fraser, P.J., Etheridge, D.M., Sturges, W.T., Vollmer, M.K., Rigby, M., Martinerie, P., Mühle,  
2293 J., Worton, D.R., Krummel, P.B., Steele, L.P., Miller, B.R., Laube, J., Mani, F.S., Rayner, P.J., Harth, C.M.,  
2294 Witrant, E., Blunier, T., Schwander, J., O'Doherty, S. & Battle, M. (2016) Atmospheric abundance and global  
2295 emissions of perfluorocarbons CF<sub>4</sub>, C<sub>2</sub>F<sub>6</sub> and C<sub>3</sub>F<sub>8</sub> since 1800 inferred from ice core, firn, air archive and in  
2296 situ measurements. *Atmos. Chem. Phys.* **16**: 11733-11754.
- 2297 Tsai, W.T. (2011) Environmental and health risks of chlorine trifluoride (ClF<sub>3</sub>), an alternative to potent greenhouse  
2298 gases in the semiconductor industry. *Journal of Hazardous Materials*, **190**: 1-7
- 2299 U.S. Environmental Protection Agency. (2009) Clean Air Act National Stack Testing Guidance. URL  
2300 <https://www.epa.gov/compliance/clean-air-act-national-stack-testing-guidance>
- 2301 US Environmental Protection Agency. (2012a) Report to EPA on Etch Factor Proposal for Fab GHG Emissions  
2302 Reporting, February 28, 2012, URL [https://www.regulations.gov/document?D=EPA-HQ-OAR-2011-0028-](https://www.regulations.gov/document?D=EPA-HQ-OAR-2011-0028-0074)  
2303 [0074](https://www.regulations.gov/document?D=EPA-HQ-OAR-2011-0028-0074)
- 2304 U.S. Environmental Protection Agency, (2012b) Technical Support for Modifications to the Fluorinated  
2305 Greenhouse Gas Emission Estimation Method Option for Semiconductor Facilities under Subpart I, Office of  
2306 Air and Radiation, URL <https://www.regulations.gov/document?D=EPA-HQ-OAR-2011-0028-0083>
- 2307 U.S. Environmental Protection Agency. (2017a) Inventory of U.S. Greenhouse Gas and Sinks: 1990- 2015, EPA  
2308 430-R-05-003. URL <https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks>



Final Draft

- U.S. Environmental Protection Agency. (2017b) 40 CFR 98 Mandatory Greenhouse Gas Reporting – Subpart A General Provision, “TABLE A–1 TO SUBPART A OF PART 98—GLOBAL WARMING POTENTIALS”, URL <https://www.gpo.gov/fdsys/pkg/CFR-2017-title40-vol23/pdf/CFR-2017-title40-vol23-part98-subpartA-appA.pdf>
- U.S. Environmental Protection Agency. (2017c) Method 1, “Method 1— Sample and Velocity Traverses for Stationary Sources”, URL [https://www.epa.gov/sites/production/files/2017-08/documents/method\\_1\\_3.pdf](https://www.epa.gov/sites/production/files/2017-08/documents/method_1_3.pdf)
- U.S. Environmental Protection Agency. (2017d) Method 2, “Method 2 - Velocity - S-type Pitot”, URL <https://www.epa.gov/emc/method-2-velocity-s-type-pitot>
- U.S. Environmental Protection Agency. (2017e) Method 320, “Method 320 - Vapor Phase Organic and Inorganic Emissions by Extractive FTIR”, URL <https://www.epa.gov/emc/method-320-vapor-phase-organic-and-inorganic-emissions-extractive-ftir>
- Wieland, R., Pittroff, M., Boudaden, J., Altmannshofer, S. & Kutter, C. (2016) Environmental-friendly fluorine mixture for CVD cleaning processes to replace C<sub>2</sub>F<sub>6</sub>, CF<sub>4</sub> and NF<sub>3</sub>. *ECS Transactions*, **72** (19) 23-34.
- World Semiconductor Council. (2011) Joint statement of the 15th meeting of the World Semiconductor Council. URL [http://www.semiconductorcouncil.org/wp-content/uploads/2016/07/WSC\\_2011\\_Joint\\_Statement.pdf](http://www.semiconductorcouncil.org/wp-content/uploads/2016/07/WSC_2011_Joint_Statement.pdf)
- World Semiconductor Council. (2012) Best practice guidance of PFC emissions reduction. URL [http://www.semiconductorcouncil.org/wp-content/uploads/2016/07/Final\\_WSC\\_Best\\_Practice\\_Guidance\\_26\\_Sept\\_2012.pdf](http://www.semiconductorcouncil.org/wp-content/uploads/2016/07/Final_WSC_Best_Practice_Guidance_26_Sept_2012.pdf)
- World Semiconductor Council. (2014) Revision of the 2013 World Semiconductor Council PFC data. URL <http://www.semiconductorcouncil.org/wp-content/uploads/2016/04/WSC-JS-Annex-III-5-November-2014.pdf>
- World Semiconductor Council. (2016) Joint statement of the 20th meeting of the World Semiconductor Council. URL <https://www.semiconductors.org/clientuploads/Trade%20and%20IP/20th%20WSC%20Joint%20Statement%20May%202016%20Seoul%20FINAL.pdf>
- Zhu, X., Sun, B., Huo, C. & Xie, H.D. (2012) Advances in abatement of perfluorocarbons with microwave plasma. *Advanced Materials Research*. 518-523: 2315-18.
- References copied from the 2006 IPCC Guidelines**
- Agnostinelli, G., Dekkers, H. F. W., DeWolf, S. and Beaucarne, G. (2004). “Dry Etching and Texturing Processes for Crystalline Silicon Solar Cells: Sustainability for Mass Production”, presented at the 19th European Photovoltaic Solar Energy Conference, Paris, 2004.
- Alsema, E. A., Bauman, A. E., Hill, R. and Patterson, M. H. (1997) “Health, Safety and Environmental Issues in Thin Film Manufacturing”, 14<sup>th</sup> European PV Solar Energy Conference, Barcelona, Spain. 1997.
- Burton, C. S. (2004a). “Uses and Air Emissions of Liquid PFC Heat Transfer Fluids from the Electronics Sector: Initial Findings”, report prepared for U. S. EPA’s Climate Change Division, October 2004.
- Burton, C. S. (2004b). “PFC Uses, Emissions, and Trends in FPD Manufacture: An Update”, draft report prepared for U. S. EPA’s Climate Change Division, June 2004.
- Burton, C. S. (2006). “Sources and Methods Used to Develop PFC Emission Factors from the Electronics Sector”, report prepared for U. S. EPA’s Climate Change Division, February 2006.
- Cowles, D. (1999) “Oxide Etch Tool Emissions Comparison for C<sub>5</sub>F<sub>8</sub> and C<sub>4</sub>F<sub>8</sub> Process Recipes”, presented at A Partnership for PFC Emissions Reductions, SEMICON Southwest 99, Austin, TX. October 1999.
- Fthenakis, V. (2005) Personal communication to S. Bartos on 5 February 2005 of data tables quantifying historical and current CF<sub>4</sub> and C<sub>2</sub>F<sub>6</sub> usage in PV manufacture for U. S. and Europe.
- Fthenakis, V. (2006) Personal communication to S. Burton and S. Bartos explaining proposal to begin monitoring FC emissions from European PV industry. Feb. 6, 2006.
- IEA (2004). ‘Trends in Photovoltaic Applications: Survey report of selected IEA Countries between 1992 – 2003’, Photovoltaic Power Systems Programme (PVPS), International Energy Agency, Report IEA-PVPS T1-13:2004, September 2004.
- IPCC (2000). Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. Penman J., Kruger D., Galbally I., Hiraishi T., Nyenzi B., Emmanuel S., Buendia L., Hoppaus R., Martinsen

- 2360 T., Meijer J., Miwa K., Tanabe K. (Eds). Intergovernmental Panel on Climate Change (IPCC),  
2361 IPCC/OECD/IEA/IGES, Hayama, Japan.
- 2362 ITRS (2004), “International Technology Roadmap for Semiconductors” available at  
2363 <http://public.itrs.net/report.htm>
- 2364 Kim, D-H., (2006) 9 January 2006 Personal communication to Hideki Nishida identifying the historical average  
2365 (50:50) proportion of SF<sub>6</sub> usage for etching and CVD chamber-cleaning in Japanese, Korean and Taiwan  
2366 TFT-FPD manufacture.
- 2367 Leu, C-H., (2004) “SF<sub>6</sub> Abatement Strategy in Taiwan”, presented at SF<sub>6</sub> Power Reduction Partnership for Electric  
2368 Power Systems, Scottsdale, Az., 1-3 December 2004.
- 2369 Leu, C-H *et al.* (2004) “PFC emissions Abatement for TFT-LCD Industry in Taiwan”, available in the Proceedings  
2370 of the 15<sup>th</sup> Annual Earth Technology Forum, Washington, D. C., 13-15 April 2004.
- 2371 Maycock, P. (2005) “PV market update: global PV production continues to increase”, Renewable Energy World,  
2372 Vol. 8 (4), pp 86-99.
- 2373 Meyers, J., Maroulis, P., Reagan, B. and Green, D. (2001). “Guidelines for Environmental Characterization of  
2374 Semiconductor Equipment”, Technology Transfer #01104197A-XFR, pub. International SEMATECH,  
2375 Austin, Texas, USA. December 2004, See: [www.sematech.org/docubase/document/4197axfr.pdf](http://www.sematech.org/docubase/document/4197axfr.pdf).
- 2376 Nishida, H. *et al.* (2004) “Voluntary PFC Emission Reduction in the LCD Industry”, available in the Proceedings  
2377 of the 15<sup>th</sup> Annual Earth Technology Forum, Washington, D. C., 13 – 15 April 2004.
- 2378 Nishida, H., Marsumura, K., Kurokawa, H., Hoshino, A. and Masui, S. (2005), “PFC emission-reduction strategy  
2379 for the LCD industry”, J. Society for Information Display, Vol 13, pp. 841-848 (2005).
- 2380 Nishida, H. (2006). 7 January 2006 Personal communication to D-H. Kim confirming historical average 50:50  
2381 proportion of SF<sub>6</sub> usage for etching and CVD chamber-cleaning in Japan, Korean and Taiwan TFT-FPD  
2382 manufacture.
- 2383 Phylipsen, G. J. M. and Alsema, E. A., (1995) “Environmental life-cycle assessment of multicrystalline silicon  
2384 solar cell modules”, report prepared for Netherlands Agency for Energy and the Environment, Report No.  
2385 95057, September 1995.
- 2386 Rentsch, J., Schetter C., Schlemm H., Roth, K. and Preu, R. (2005). “Industrialization of Dry Phosphorous Silicate  
2387 Glass Etching and Edge Isolation for Crystalline Silicon Solar Cells”, Presented at the 20<sup>th</sup> European  
2388 Photovoltaic Solar Energy Conference and Exhibition, Barcelona, Spain. 6-10 June, 2005.
- 2389 Sekiya, A. (2003). “Climate-Friendly Alternative Refrigerant and the Others: New Evaluations for sustainability”,  
2390 The Earth Technologies Forum, Washington, D. C., 23 April, 2003.
- 2391 Shah, A., Meier, J., Buechel, A., Kroll, U., Steinhäuser, J., Meillaud, F. and Schade, H. (2004). “Toward Very  
2392 Low-Cost Mass Production of Thin-film silicon Photovoltaic (PV) Solar Modules on Glass”, presented at  
2393 ICCG5 Conference in Saarbrücken, Germany, July 2004.
- 2394 SIA (2000). “Equipment Environmental Characterisation Guidelines”, Revision 3.0, Semiconductor Industry  
2395 Association (SIA), San Jose, California, USA, February 2000
- 2396 Strategic Marketing Associates (2004a). WORLD FAB WATCH: The Industry’s Encyclopedia of Wafer Fabs  
2397 Since 1994, January 2004 Edition.
- 2398 Strategic Marketing Associates (2004b). WORLD FAB WATCH: The Industry’s Encyclopedia of Wafer Fabs  
2399 Since 1994, October 2004 Edition.
- 2400 Tuma, P.E. and Tousignant, L. (2001). “Reducing Emissions of PFC Heat Transfer Fluids,” Presented at Semicon  
2401 West, San Francisco, July 2001.
- 2402 U.S. EPA (2005). U.S. Environmental Protection Agency, Inventory of U.S. Greenhouse Gas and Sinks: 1990-  
2403 2003, EPA 430-R-05-003, April 2005.
- 2404