PFC, HFC, NF_3 AND SF_6 EMISSIONS FROM SEMICONDUCTOR MANUFACTURING

ACKNOWLEDGEMENTS

This paper was written by Scott C. Bartos (USEPA) and C. Shepherd Burton (ICF, Incorporated). Several reviewers made valuable comments on draft versions of this paper, including Sally Rand (USEPA), Bill Irving (USEPA), and Dina Kruger (USEPA).

ABSTRACT

Six fully fluorinated compounds and one hydrofluorocarbon are widely used by the semiconductor industry: tetrafluoromethane (CF_4), hexafluoroethane (C_2F_6), octafluororopane (C_3F_8), octafluorobutane (c-C_4F_8), suflur hexafluoride (SF_6) nitrogen trifluoride (NF_3) and trifluoromethane (CHF_3)[1]. Collectively, these gases will be termed fully fluorinated compounds (FFCs) for ease of discussion in this paper. Semiconductor manufacture uses FFCs in two critical processes: for cleaning chemical vapour deposition (CVD) chambers and for dry etching. Depending on the complexity of the product, the manufacturing process may require up to 100 FFC-using steps and up to 3 months process time. The *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC Guidelines)* do not provide specific guidance on how to estimate FFC emissions from semiconductors.

Good practice in inventory preparation for the semiconductor industry presents challenges at all levels: factory, national and third party verification. At the factory level, estimation of potential emissions based on production capacity or FFC use may introduce inaccuracies due to a number of factors related to the complexity of the production process, the variability of emissions with product types, and the rapidity with which processes change in this dynamic industry. For similar reasons, measurement of actual FFC emissions from semiconductor manufacture is extremely challenging, and depending on the level of accuracy desired, potentially very costly. Through voluntary programmes, a significant portion of the global industry is endeavouring to estimate annual FFC emissions. Several facility level emission measurement methods have been devised and used. Through the efforts of the World Semiconductor Council, industry leaders in Europe, Japan, Korea, Taiwan and the United States are working towards adopting a common emission measurement method.

At the national level, there is no common inventory method currently in use, and reporting has been problematic for this source. It appears that some countries have not reported FFC semiconductor emissions, and reports of other Parties lack transparency (UNFCCC/SBSTA/1998/7). Currently, emissions are reported under the IPCC category 2F6 Other (Industrial Processes Halocarbon/SF_6 Consumption). Because there are a number of FFCs used in semiconductor manufacture, with different global warming potentials (GWPs) and in different quantities, emissions of different species cannot be summed and reported on a mass basis. They can be aggregated on a carbon equivalent basis, but this does not allow for reconstruction of the inventory since a third party will not know the share of each gas. Unless reporting of semiconductor emissions under “Other” is explicitly specified there may be problems with transparency because emissions from other undesignated industrial sources such as SF_6 used by electrical utilities would also be reported on this line.

Industry concern for confidential business information may complicate the desire for clear and transparent national reporting. Many semiconductor manufacturers consider chemical purchase and emission information as proprietary data. Countries may need to establish a confidential data tracking and reporting system to ensure sensitive data is not released to the public or presented in a way that reveals company-specific information. Unless a country has fewer than four manufacturers, aggregation of data should eliminate any concerns of revealing proprietary process information. CVD and etch tool manufacturers also consider tool-specific emissions characterizations as proprietary. Depending on the emissions estimation method used, this may make documentation and third party evaluation difficult.

[1] Several other HFCs, including difluoromethane (CH_2F_2) and 1,1,1,2-tetrafluoroethane ($C_2H_2F_4$) also find some application; however, their use is less than 1% of the total, and so they will not be further considered here.

Quality Assurance/Quality Control activities will need to occur at several steps in the process. At the factory level, key elements are internal quality control on factory-level emissions, and documentation of data and methods for reviewers. The inventory agency must ensure the accuracy of factory submissions as well as the aggregated inventory. The inventory agency is also responsible for providing documentation and reporting sufficient information to the UNFCCC. One or more different types of external reviews and audits may also be appropriate for semiconductor inventories, and each will require complete documentation.

The desired outputs and key questions related to these three areas have been discussed broadly in the general background paper, and are summarized in a short paper entitled, "Outputs and Questions for Breakout Groups."

1 INTRODUCTION

1.1 Nature, magnitude, and distribution of source

Semiconductors or integrated circuits act as the brains for advanced electronic controls and devices, which have become increasingly prevalent in consumer and industrial equipment in recent years. Computers, for example, contain information controllers, memory and processing devices, and they are also found in vehicles, appliances, buildings, and industrial processes. The use of fully fluorinated compounds (FFCs) in the semiconductor industry first began to occur in the late 1970's; however, their use did not become widespread until the late 1980s or early 1990s, as a result of the need to create increasingly smaller more complex devices. As the industry continued its practice of exponentially increasing the functionality of semiconductor devices by making them simultaneously smaller and more powerful, new manufacturing processes were needed. The processes that allowed manufacturers to create these smaller, more complex features rely on FFCs for both cleaning and etching functions. Six fully fluorinated compounds (FFCs) and one hydrofluorocarbon are currently widely used by the semiconductor industry: tetrafluoromethane (CF_4), hexafluoroethane (C_2F_6), octafluororopane (C_3F_8), octafluorobutane (c-C_4F_8), suflur hexafluoride (SF_6) nitrogen trifluoride (NF_3) and trifluoromethane (CHF_3)[2]. Information on these chemicals is summarized in Table 1.

TABLE 1

SEMICONDUCTOR PROCESS GASES

Species	Chemical Formula	Atmospheric Lifetime (years)	Global Warming Potential (100 year time horizon)
Perfluoromethane	CF_4	50,000	6,500
Perfluoroethane	C_2F_6	10,000	9,200
Perfluoropropane	C_3F_8	2,600	7,000
Perfluorocyclobutane	c-C_4F_8	3,200	8,700
Trifluoromethane (HFC-23)	CHF_3	264	11,700
Nitrogen Trifluoride	NF_3	740	8,000
Sulfur Hexafluoride	SF_6	3,200	23,900

1.1.1 Description of FFC use

Manufacturing semiconductor devices is complex, and FFCs are used at several points in the process[3.] The manufacturing process begins with a semi-conductive crystalline wafer, usually made of silicon. This wafer travels through a dust and particle-free production area called a clean room, cycling through various pieces of manufacturing equipment or "tools". Many of these tools deposit thin layers of insulating and conductive materials via chemical vapour deposition (CVD) and etch intricate patterns into the successive layers of insulating films and metal. The patterned insulating metal layers act to connect (i.e., to wire together or integrate) the active components that comprise the device or integrated circuit (IC). A single wafer, from start to finish, may require as many as 100 distinct FFC-utilizing process steps, and up to 3 months of process time.

FFCs are used for both plasma cleaning of CVD chambers and plasma (dry) etching of the thin insulating and metal layers. The FFCs allow manufacturers to accurately etch the submicron-scale patterns on these metal and dielectric layers and perform rapid chemical cleaning of CVD tool chambers. The carbon and fluorine that these compounds deliver in a plasma are essential when etching advanced integrated circuits because, in addition to etching, they form polymers, which allow for highly selective and anisotropic (directional) film removal.

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[2] Several other HFCs, including difluoromethane (CH_2F_2) and 1,1,1,2-tetrafluoroethane ($C_2H_2F_4$) also find some application; however, their use is less than 1% of the total, and so they will not be further considered here.

[3] Much of the material presented in this Section may be found in Burton and Beizaie, "EPA's PFC Emissions Vintage Model (PEVM) v. 2.14: Deswcription and Documentation", prepared for USEPA, Office of Atmospheric Programs, 1200 Pennsylvania Avenue, NW, Washington, DC 20460 (November 2001).

Chemical vapor deposition (CVD) chambers – often called CVD tools – are the industry workhorses for depositing materials that will act as insulators and wires. Commonly deposited CVD films include polycrystalline silicon, silicon nitride, silicon dioxide, and metals such as tungsten. To eliminate buildup of these materials on internal chamber parts and the concomitant risk of contamination, periodic chamber cleans must be performed. CF_4, C_2F_6, C_3F_8 and NF_3 are the usual FFCs used in chamber cleaning. During the clean cycle, the FFC is converted to F atoms in a plasma, which chemically etches away residual material from chamber walls, electrodes, and chamber hardware. However, due to the low destruction efficiency (high dissociation energy) of FFCs, a portion of the gas flowing into the chamber during the clean is not dissociated into F-atoms and, therefore, not used to clean the chamber: that unreacted portion flows through the chamber and, unless emission abatement technologies are used, eventually into the atmosphere. Of the total FFC emissions from semiconductor manufacturing, roughly >60 percent (million metric tons of carbon equivalent or MMTCE basis) results from chamber cleaning steps.

Once the electronic components (e.g., transistors) have been fabricated in the silicon, thin conducting material is added – the minute wires – to interconnect individual circuit components. In complex devices the length of this wiring will exceed 4 km per cm^2 of device area. The pathways for these wires are etched into the insulating layers using another industry workhorse – etch chambers or etch tools. These etch tools also use FFCs in a plasma. In etch tools, both F-atoms and polyatomic species such as CF2 are created and react at the film surface (following prescribed patterns) to selectively remove (etch) substrate material. Etch processes are used to form, for example, trenches that are subsequently filled with metal to form the wires. CF_4, CHF_3, C_2F_6, C_3F_8, c-C_4F_8, NF_3 and SF_6 are etching gases. In some etching processes it is important that certain CF-containing polymers are formed on surfaces, which permits highly selective and directional removal of film material. So, depending on the etch process, either CF-containing FFCs are used or simply SF_6. In etch processes, on average, more of the FFCs is utilized, so less of the original FFC exits the chamber unreacted and is emitted into the atmosphere. Of the total FFC emissions from semiconductor manufacturing, roughly <40 percent (MMTCE basis) result from plasma etching steps.

In addition to being directly used in manufacturing processes, FFCs can also be transformed during cleaning and etch processes. Put simply, during the process, an FFC input of one gas can be transformed into a different FFC which is exhausted to the atmosphere. For example, when either CHF_3 or C_2F_6 are used in either cleaning or etching CF_4 is generated and emitted as a process by-product. In the C_2F_6 case, the amount of CF_4 produced can be 10% to 30% of the C_2F_6 input volume depending on the cleaning process. In the case of CHF_3, reports indicate that approximately 10% (volume) of the input CHF_3 is converted to CF_4 and smaller yields of C_2F_6 have also been measured.

A medium size U.S. manufacturing plant (called a "fab") has approximately 60 etch and CVD tools. For a large fab, the number of etch and CVD tools increases, ranging from 100 – 200[3,4]. Of the total number of tools, roughly 60 percent are for etching and 40 percent are used to produce thin films via CVD. A large fab may have a production capacity of approximately 360,000 to 480,000 eight-inch wafers per year and may manufacture approximately 70 - 300 million chips, depending on product yield, feature size, and chip size. Annual FFC emissions for a fab can range between 0.001 to 0.05 MMTCE.

Since its inception, the semiconductor industry has successfully developed "smaller and faster" products. Smaller circuit components operate faster, require less energy and generate less heat. State-of-the-art semiconductors incorporate circuitry with feature sizes approaching 0.18µm, which decreases by a factor approximately 0.7 every 2 – 3 years. The complexity of these products increases as manufacturers continue to shrink feature sizes. Circuit designers use multiple layers to interconnect the densely packed circuit components. Each layer of metal (wiring) and dielectric (insulating) material that is deposited and patterned upon the wafer requires specific FFC process steps. Thus, the complexity of a semiconductor product qualitatively correlates with the required number of CVD and etch (i.e., FFC-utilizing) process steps. Generally, as semiconductor devices increase in complexity, so does the quantity of FFCs (per square centimeter of silicon) required for manufacture.

It has been reported that semiconductor manufacturers also use FFCs in heat transfer applications. Companies that manufacture flat panel displays and microelectronic mechanical systems (MEMS) also use FFCs in plasma applications that are similar to those of the semiconductor industry. There is little published information about these two applications and their utilization of FFCs.

[4] Individual semiconductor manufacturing tools can have multiple FFC-using chambers. Presently, a single tool can have from one to four process chambers but the number of chambers alone does not directly relate to emissions.

1.1.2 Magnitude of FFC emissions

There is limited published information on the magnitude or trend of global FFC emissions from the semiconductor industry. Available information on the U.S. industry may provide some insights, however, and thus this section describes the U.S. situation.

Sales of FFCs to the U.S. semiconductor industry over the 1990-1996 period show a compounded annual growth rate across all species of approximately 30 percent. In 1996 approximately 1000 tons (900 metric tons) of FFCs were purchased by the U.S. semiconductor industry for use at approximately 170 fabs [5]. Prior to 1990, FFC sales to the U.S. semiconductor industry were very small, less than 100 tons per year. This rapid growth in FFC use is due to: (a) increased worldwide demand for semiconductor devices, (b) the increase in semiconductor device complexity, and (c) the lack of viable alternatives to FFCs.

The *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1996* reports FFC emissions for 1996 at 1.4 million metric tons of carbon equivalent.. The U.S. 1996 Inventory method used gas-specific U.S. sales figures, gas-specific average market prices and estimates of weighted average gas-specific emission factors to (approximately) account for the variation in use between chamber clean and etch processes. This estimate of 1.4 MMTCE appears comparable to the corresponding 1996 emissions estimates provided by the U.S. Environmental Protection Agency's (EPA) voluntary semiconductor industry partners after adjusting for the fraction of U.S. FFC sales attributable to the partnership's participants.

Using the 1996 U.S. emission estimation method, the corresponding estimate for global semiconductor industry FFC emissions is 3.9 MMTCE (based on world FFC sales to the industry and using the same average market price and emissions factors)[6]. Anecdotal reports from gas suppliers indicate that global and U.S. growth rates of FFCs purchases slowed somewhat beginning in late 1997, which is attributed to slowing demand for advanced semiconductors devices.

1.1.3 Distribution of semiconductor industry sources

Semiconductors are produced by approximately 400 organizations around the world in 1,100 fabs ranging in size from small research and development sites to large production plants. The manufacturing capacities of these fabs can vary by a factor of up to 300. Approximately 150 of these organizations currently operate the 350 fabs in the U.S., of which approximately 280 are pilot and production fabs operated by or for the U. S. Government and commercial companies. Not all fabs use large quantities of FFCs to manufacture semiconductor devices due mostly to their size and/or product distribution. For example, it is estimated that approximately two-thirds to three-fourths of the FFC emissions from the U. S. semiconductor are generated by approximately 40 percent of the 350 fabs.

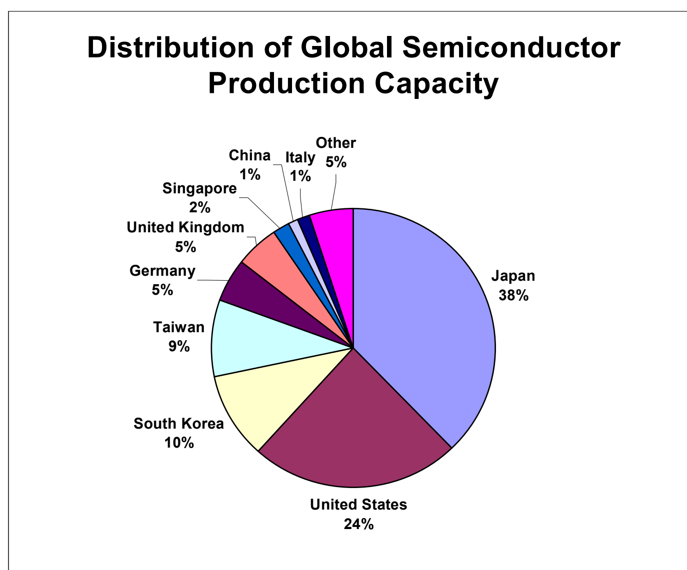
As a general rule of thumb, semiconductor devices with feature sizes 1µm and smaller are major users of FFCs. Figure 2 depicts the distribution of world semiconductor production capacity of devices with feature sizes 1µm and smaller by country for 1996 (expressed as percentage of potential total silicon production). This distribution may be considered a rough approximation or proxy of the distribution of potential FFC emissions from world semiconductor manufacturing. In descending rank order, the countries with the top capacities are: Japan, United States, South Korea, Taiwan, United Kingdom and Germany (tied at 5 percent each), Singapore, China and Italy (tied at one percent each), which in the aggregate account for approximately 95 percent of global production capacity.

Unlike some industrial processes, neither semiconductor production capacity nor sales data is a good proxy for actual emissions. Actual emissions vary with plant utilization, product type and complexity. For example, one fab may manufacture a different distribution of products or more chips of greater complexity than a similar fab manufacturing an identical volume of silicon (and therefore require a different distribution of and/or greater volume of FFCs in their manufacture).

[5] The distribution (wt %) of the 1996 purchases and the corresponding 1992 – 1996 compound average growth rates (%), provided parenthetically, for each of the seven gases of interest are: CF_4 = 28 (38), CHF_3 = 11 (38), C_2F_6 = 47 (35), C_3F_8 = 0.4 (25), C_4F_8 = 0 (0), NF_3 = 4 (35), and SF_6 = 9 (20).

[6] Estimates for the European countries were obtained by allocating an estimate for Europe's total emissions according to country-specific potential silicon production capacities.

Figure 2 1996 global production capacity for semiconductor devices with feature seizes less than or equal to 1 micron



Source: SEMI International Fabs.on Disk, October 1998

Work recently presented by Beu and Brown (1998) suggests that the distribution of FFC use by manufacturing process (i.e., CVD clean vs. etch) may be an important consideration in estimating FFC emissions [7]. In this paper, the authors compare the differences in FFC emissions estimates using methods of varying complexity. Beu and Brown present a "typical" fab with unabated FFC emissions that total 0.036 MMTCE (or about 2 percent of the 1996 U.S. total). The range in average gas-specific emissions across the seven gases identified in Table 1 (See Summary above) is 1% (for C_4F_8) to 48% (for C_2F_6) (MMTCE basis) of the total 0.036 MMTCE for both clean and etch processes using the method for estimating emissions preferred by the authors [8]. The variability in average gas-specific emissions (MMTCE) for either the plasma clean or plasma etch processes is even greater, 0 (for NF_3) to 66% (for C_2F_6) for the total emissions from plasma clean processes and 3% (for both C_3F_8 and C_4F_8) to 59% (for SF_6) of the total emissions from the plasma etch processes. With such variability, care is needed in forming and interpreting averages.

Collecting gas usage data and determining process-specific emissions factors is a complex task for the semiconductor industry. When determining gas usage, it is very important that the residual gas left in "empty" cylinders (known as the heel) and returned to the chemical supplier be accounted for accurately[9]. Other important factors such as the types of FFCs used and process specific emission factors change frequently with process improvements in this dynamic and competitive industry. Data collection of this type is more difficult for this industry than industries where manufacturing processes and technologies are less variable.

1.2 The current state of inventory methodologies

At the national level, there is no common inventory method currently in use, and reporting has been problematic for this source. The methods, assumptions and data used to estimate FFC emissions from semiconductor manufacture in the National Communications are not clear, transparent or well documented. The lack of transparency and

[7] Beu, L. and Brown, P. T., *An Analysis of International and U.S. PFC Emissions Estimating Methods* presented at SEMICON SouthWest 98, Austin, Texas, USA, October 1998.

[8] It is important to keep in mind that the emissions factor from the use of any specific gas represents an average taken over several tools used to etch various films or to clean chambers after the production of various films. Thus, emission estimates and emissions factors used to estimate emissions are, strictly speaking, weighted according to the amount of a specific gas used by that tool for a specific process.

[9] At this time the fate of the residual FFCs is not certain. A portion of the residual gases may be vented directly to the atmosphere.

supporting documentation of methods and data makes review and verification impossible. It is unclear whether all countries with semiconductor industries have reported FFC emissions (UNFCCC/SBSTA/1998/7).

In part, problems with estimating emissions from this source may arise because the *IPCC Guidelines* do not provide specific guidance on how to estimate FFC emissions from semiconductors. The *IPCC Guidelines* do, however, describe two general methods for estimating emissions from industrial sources, which can be applied to the semiconductor industry as follows:

- Tier 1 (potential emissions): national FFC usage in the country based on supply and trade data), and
- Tier 2 (actual emissions): actual FFC usage emission factor, for each FFC, potentially including direct reporting of actual FFC emissions estimates by all sources

The United States, Japan, Europe, Korea and Taiwan have established national/regional voluntary action plans or partnerships to estimate and report annual FFC emissions using various methods resembling either Tier 1 or Tier 2 methodologies. These voluntary programmes represent the most developed emissions estimating methods currently available but no one method is used consistently from country-to-country.

The World Semiconductor Council (WSC), which represents semiconductor industry associations from the U.S., Japan, Europe, Korea, and Taiwan, has made FFC emissions reduction its primary environmental concern and has begun evaluating the various emission estimating methods practiced by its members. The WSC has adopted a common method and practice for estimating FFC emissions. Although not all manufacturers participate in the WSC, if successful, this initiative would result in a fairly large set of comparable emissions data for this sector.

2 METHODOLOGICAL ISSUES

2.1 Selection of good practice methods

As discussed above, the IPCC's general methods can be used in several ways to estimate emissions from the semiconductor industry. At the most basic level, countries have a choice between using a Tier 1 (potential) method, or a Tier 2 (actual) method. Within Tier 2, there are several possible approaches that vary in terms of accuracy and resource requirements. Each of the broad approaches is described below, and summarized in Table 2.

TABLE 2

METHODS TO ESTIMATE EMISSIONS FROM THE SEMICONDUCTOR INDUSTRY

Estimating Method	Data Requirements	Method Features
Tier 1 (Potential)	FFC purchase data	Very simple and precise Highly inaccurate
Tier 2: Level 1 Simple	National emissions factor for all gases and processes – individual factors may be supplied by tool manufacturers FFC purchase data	Emissions factor will require annual re-evaluation Still inaccurate, since specific processes are not reflected in emission factors Country specific conventions for FFC byproducts/returned gas
Tier 2: Level 2 Average	"Average" emission factors by gas and process type (CVD and etch) FFC usage data by process/gas	Detailed, annual survey/analysis required to determine emission factors Still fails to consider differences amongst specific fab-level or tool-level processes
Tier 2: Level 3 Specific	Specific emission factors for each fab process/tool Fab-level (or process level) gas usage	Most labor intensive and costly in terms of data collection Most accurate

Tier 1: Potential Method

Under Tier 1, it is assumed that FFC emissions are equal to their use by the semiconductor industry. Thus, for this method, it is necessary to obtain data on annual FFC-specific gas usage (purchase less unused) by the industry. While this method could be used when actual emissions data are unavailable, the resulting estimate is likely to be inaccurate (i.e., overstate emissions) by as much as a factor of two. This method fails to account for both gas utilization during the manufacturing process and the potential transformation of input FFCs into

different FFCs during the process. Acquiring the gas usage data may also present difficulties, although either market surveys or reporting by semiconductor manufacturers (or gas producers) could be undertaken.

Tier 2: Actual Method

Three broad approaches are possible for estimating emissions using a Tier 2 method. Currently, Levels 1, 2, 3 are being further evaluated by both industry and government. Levels 1 and 2 represent a technical compromise relative to Level 3, which is the most advanced method. The principal technical issue in the choice between Levels 1, 2 and 3 is the amount of aggregation of parameters that is necessary.

Level 1: Simple Mass Balance

Tier 2, Level 1 is a simple mass balance approach that essentially adjusts the Tier 1 estimates to take into account the fact that all FFC purchased by the semiconductor industry is not emitted. Under this method, gas purchase data is multiplied by gas-specific emission factors that reflect the fate of the gas during device manufacture. While this method is more accurate than Tier 1, it relies on several broad assumptions. First, use of a single emission factor for all FFCs within a country vastly oversimplifies the highly variable nature of FFC use within the industry. Second, careful consideration would need to be given to this factor to ensure that it appropriately accounts for both the destruction and the transformation of FFCs within the process. Third, unused gas (i.e., cylinder heel) must be accounted for when developing the emissions factor. Finally, as with Tier 1, acquiring gas usage data may be challenging.

Level 2: Average Mass Balance

The Tier 2, Level 2 method attempts to address some of the weaknesses in Level 1 by obtaining additional data. Under this approach, “average” emission factors for each gas would be developed for the two broad process types, etch and clean, rather than using a single national factor for each gas. A factor representing the “average” quantity of unused gas and an FFC byproduct formation factor should improve this method’s accuracy. In this way, differences in by-product formation and specific gas usage for etch and clean processes could be reflected. While this approach should be more accurate than Level 1, it will require much more detailed data on gas usage at the process level and that may be costly to track and gather in either medium or large fabs. In forming averages, appropriate consideration should be given to weighting the factors and usage quantities.

Level 3: Specific Mass Balance

Tier 2, Level 3 is the most accurate and data-intensive approach. Under this approach, specific FFC emission factors are developed for each gas and tool/process in a fab, from direct one-time utilization measurements under actual production process conditions.

The FFC emissions from a specific tool are estimated using tool/process-specific estimates of FFC utilization. Utilization (a fraction) is the measured quantity of FFC utilized or chemically altered during a clean or etch process. The complement of utilization (1- utilization) is called the tool’s emissions factor for the specific process conditions. Changes in process- to improve product quality, yield, throughput, etc.- will affect utilization and emissions. Recently tool manufacturers and fabs began implementing process changes to increase FFC utilization (i.e., decrease emissions). Process changes made by both tool manufacturers and by fabs that increase utilization could be adopted, provided compromises (if any) in quality, yield and throughput are acceptable. These utilization factors are secrets closely guarded by both tool manufacturers and semiconductor manufacturers.

This method can directly account for FFC by-product formation and actual (or engineering estimates of) FFC-specific usage for that tool/process. The challenge in this approach is that it requires tracking and gathering of large amounts of data, which may represent a substantial cost from a fab’s perspective that does not improve the quality or efficiency of the products it is designed to produce. The high administrative burden and potential cost appear to be the principal detractions from its adoption.

2.2 Emissions factors

In the context of the semiconductor estimates, emission factors refer to the FFC output per unit FFC input. As the discussion of methodologies indicates, developing emission factors for this industry is extremely complex. Unlike some industrial sources, direct continuous measurement of emissions is not currently viable for this industry.

Measurements of emissions factors (averaged over several production simulations) are provided to semiconductor manufacturers by the tool manufacturers under terms of nondisclosure. Gas suppliers also make emissions factor measurements, either under contract to the tool manufacturers or to the fab. These measurements are typically made under what is called centerline (or nominal) process conditions (i.e., nominal flow, power and

pressure, etc. settings). However, once operating in full production, many manufacturers alter process conditions from the centerline conditions.

Although tool specific information is held confidential by tool and semiconductor manufacturers, it is generally accepted that FFC gas utilization varies widely by tool and process. For example, for SF_6 used in an etch process, utilization is believed to range between 5% and 50% (volume). Reports of CF_4 utilization, depending on whether the CF_4 is used in cleaning or etching processes (and in the case of etching with other FFC gases), vary between 5% and 20%.

The transformation of FFCs during manufacturing processes must also be accounted for. As mentioned previously, when either CHF_3 or C_2F_6 are used in either cleaning or etching, CF_4 is generated and emitted as a process by-product. In the C_2F_6 case, the amount of CF_4 produced can be 10% to 30% of the C_2F_6 input volume depending on the cleaning process. In the case of CHF_3, reports indicate that approximately 10% (volume) of the input CHF_3 is converted to CF_4 and smaller yields of C_2F_6 have also been measured.

The situation is even more complex because many clean and etch processes use FFC gas mixtures. For example, mixtures of C_2F_6 and NF_3 are used in some cleaning processes and in some etch processes mixtures of CHF_3 and CF_4 or mixtures of CHF_3 and SF_6 are used. In these instances, not only does utilization change from the single gas case, but the product formation yields change also.

Because many fabs use multiple etch processes and several cleaning processes, developing and using a single average emission factor for one fab may not be appropriate for another, even if operated by the same company. Estimating an appropriate emission factor for all FFC gases used in a fab that makes several products using different processes is a complex data gathering exercise.

2.3 Activity level data

For this sector, activity data refers to FFC gas usage. The use of Tier 1 and Tier 2 methodologies presumes that activity level (i.e., gas usage) data is available. It is not evident that FFC gas usage data is maintained by countries and, if it is, with breakout for the semiconductor industry. The use of SF_6 for example by the Semiconductor industry is small compared to the use by either electrical utilities or magnesium producers, assuming that either of these industries operate in that country. There may be similar problems for the other FFC gases.

2.4 Uncertainty

Parallel to the IPCC sector-specific workshops on good practice guidance, the IPCC is completing a programme of work on emissions inventory uncertainty. This work will result in recommendations to the IPCC on approaches to assessing and managing uncertainty. During the IPCC Inventory Experts Group Meeting in Paris (October 1998), technical experts in the uncertainty programme developed a series of questions to be answered in the sector workshops. These questions are presented in the general background paper. The sector workshops should provide answers to these questions in the individual source context, to inform work of the uncertainty programme on establishing a general methodological approach.

2.5 Completeness

The IPCC Inventory Experts Group Meeting (October 1998) reported that national inventories of FFC emissions displayed varying levels of completeness. The semiconductor industry is not identified as a category of FFC emissions in the *IPCC Guidelines* (see for example, Section 2.17, Table 2-26). There is, therefore, no description provided by the IPCC about this source and its processes that produce atmospheric emissions of FFCs. A suggested reporting format is described in section 3 below.

The broad global distribution of fabs in more than 25 developed and developing countries presents a challenge to constructing a global emissions estimate for this industry. A useful tool for identifying semiconductor fabs by country is the *International Fabs on Disk* database, made available and updated quarterly by Semiconductor Equipment and Materials International (SEMI). Complete inventory reports would include emissions estimates for all fabs using FFCs. This subset of a country's industry must first be identified. The general rule mentioned above relating FFC use to fabs manufacturing devices with feature sizes less than or equal to 1µm is most likely not precise enough for this determination. Confirmation through discussions with individual manufacturers may be useful.

Current annual emissions from U.S. fabs range between approximately 0.001 to 0.05 MMTCE, or between roughly 0.05 to 2 percent of the annual 1996 estimate of total FFC emissions from the u.s. semiconductor industry. The only u.s. companies that appear to be estimating FFC emissions are participants in the EPA partnership, which in total account for approximately 70 percent of the total u.s. semiconductor industry's FFC emissions (see Table 3).

TABLE 3

PARTNERS IN THE US ENVIRONMENTAL PROTECTION AGENCY'S PFC EMISSION REDUCTION PARTNERSHIP FOR THE SEMICONDUCTOR INDUSTRY

• Advanced Micro Devices	• Micron Technology, Incorporated
• American Microsystems, Incorporated (AMI)	• Motorola, Incorporated
• Burr-Brown Corporation	• National Security Agency
• Cherry Semiconductor Corporation	• National Semiconductor Corporation
• Digital Equipment Corporation	• NEC Electronics Incorporated
• Dominion Semiconductor, LLC	• Philips Electronics North America Corporation
• Eastman Kodak Company	• Rockwell Semiconductor Systems
• Hewlett-Packard Company	• STMicroelectronics, Incorporated
• Hitachi Semiconductor	• Sony Semiconductor Company of America
• Intel Corporation	• Symbios Logic, Incorporated
• International Business Machines Corporation	• Texas Instruments, Incorporated
• LSI Logic Corporation	• VLSI Technology, Incorporated
• Lucent Technologies, Microelectronics Group	Several more companies are considering joing the partnership

As of January 19, 1999, the twenty-five (25) companies have joined the voluntary programme.

2.6 Other important issues

2.6.1 New gases

This dynamic industry continues to explore and develop new chemicals and materials that will allow it to construct the next generation of superior products. Good inventory practice could include a mechanism for evaluating and reporting FFCs currently in use (e.g. NF_3) and future generations that are not listed in current IPCC assessments.

2.6.2 Baseline issues

Experts should consider whether establishing a consistent time series for these estimates will be a problem.

3 REPORTING AND DOCUMENTATION

3.1 Current IPCC reporting guidelines

The *IPCC Guidelines* are used to guide countries in the preparation and submissions of annual greenhouse gas emissions inventories to the UNFCCC. The Guidelines establish:

- Standard tables, definitions, units, and time intervals for reporting all types of emissions;
- The necessary documentation to enable comparison of national inventories, including worksheets, reconstruction of the inventory from national activity data and assumptions; and
- An uncertainty assessment.

FFC emissions from semiconductor manufacture would be reported in *IPCC Table 2: Sectoral Report for Industrial Processes*, which fits into the following classification scheme (Tables.13):

Industrial Processes

2F : Consumption of Halocarbons and Sulphur Hexafluoride

2F6 : Other

Currently the table does not have a unique entry for semiconductor manufacture, nor does it have chemical specific entries. Unless reporting of semiconductor emissions under "Other" is explicitly specified there may be problems with transparency because emissions from other undesignated industrial sources such as SF_6 used by electrical utilities would also be reported on this line. Because there are a number of FFCs used in semiconductor manufacture, with different global warming potentials (GWPs) and in different quantities, emissions of different species cannot be summed and reported on a mass basis. They can be aggregated on a carbon equivalent basis, but this does not allow for reconstruction of the inventory since a third party will not know share of each gas.

In addition to the lack of transparency in the emissions estimates reported, there is also a lack of clarity on how estimates are calculated and what assumptions have been made. Issues to consider in order to address this issue include:

- Reporting of the estimation methodology;
- Reporting of the source and nature of activity data and emissions factors; and
- Reporting on QA/QC procedures.

3.2 Confidential business information

The issue of confidential business information may complicate the desire for clear and transparent national reporting. Company-specific FFC emissions from the semiconductor industry, in either aggregated (across all FFCs and country-specific fabs) or disaggregated form (by FFC and fab), represent very sensitive information, which the industry believes to convey business-sensitive knowledge to competitors about manufacturing processes and production volumes. The industry competes on the basis of quality, cost, time to market, customer need, and innovation. Countries may need to establish a confidential data tracking and reporting system to ensure the accuracy of reporting. Unless a country has fewer than four manufacturers, aggregation of data should eliminate any concerns of revealing company-specific proprietary process information.

The industry's suppliers of process equipment and gases are similarly competitive, considering tool and process-specific emissions profiles as proprietary. Depending on the emissions estimating method used, this may make third party evaluation difficult.

4 INVENTORY QUALITY

4.1 Introduction

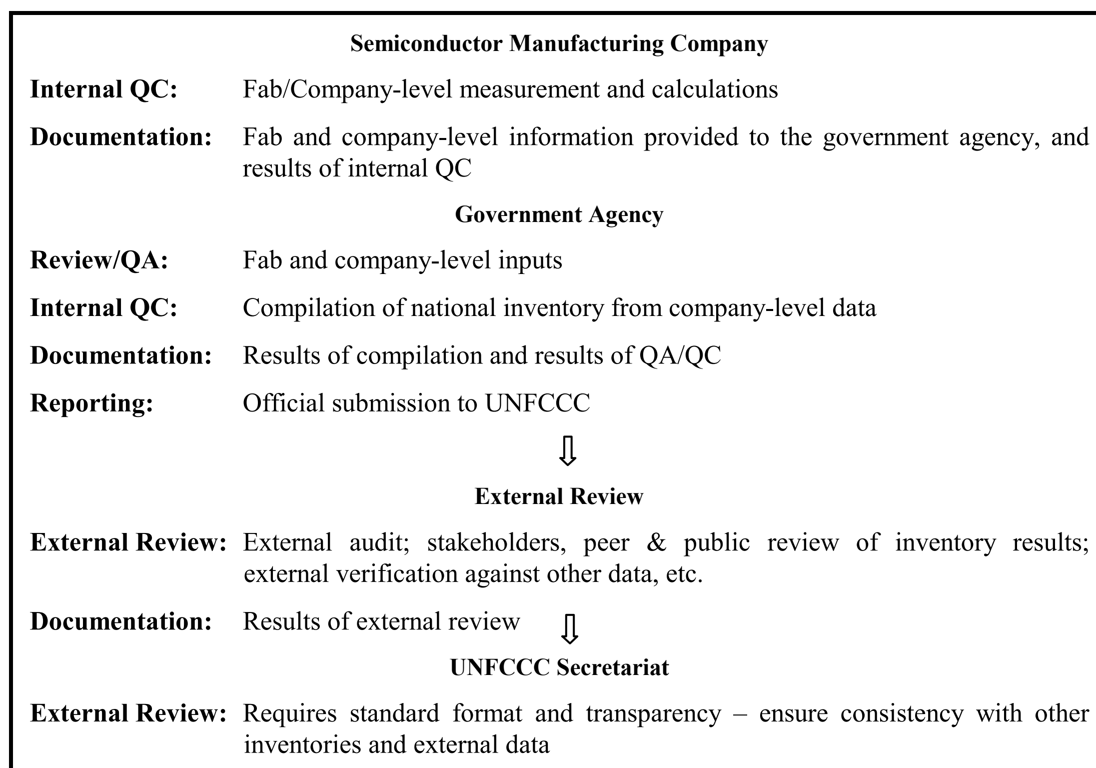
Inventory quality assurance/quality control (QA/QC) is a process that encompasses national inventory, company-level estimation, and third-party review. A well-developed and well-implemented quality assurance programme fosters confidence in the final inventory results. The common thread throughout the quality assurance process is the need for thorough documentation and complete transparency. In fact, documentation and transparency are intrinsic to QA/QC and should not be discussed separately. For example, a government agency responsible for compiling the national semiconductor industry FFC emissions inventory needs to receive sufficient documentation of plant-level data and calculations in order to perform its own QA. It also needs to document the national compilation process and the QC performed on plant data so that it is transparent to external reviewers and the UNFCCC. In short, each group should have the necessary information with which to fulfill its function. Figure 3 outlines the flow of information, and the inventory quality process at each step.

4.2 Internal inventory QA/QC systems

4.2.1 Fab/Company-level activities

A QA/QC system at a fab that directly reports its FFC emissions to the government would likely include documentation of the method for estimating emissions, storage of the raw information for ease of retrieval and sample calculations of reported results. Fabs should also document the QA/QC for gas use tracking systems.

Figure 3 Key steps in the inventory QA/QC process



Semiconductor Manufacturing Company

Internal QC:	Fab/Company-level measurement and calculations
Documentation:	Fab and company-level information provided to the government agency, and results of internal QC

Government Agency

Review/QA:	Fab and company-level inputs
Internal QC:	Compilation of national inventory from company-level data
Documentation:	Results of compilation and results of QA/QC
Reporting:	Official submission to UNFCCC

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External Review

External Review:	External audit; stakeholders, peer & public review of inventory results; external verification against other data, etc.
Documentation:	Results of external review

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UNFCCC Secretariat

External Review:	Requires standard format and transparency – ensure consistency with other inventories and external data

4.2.2 Inventory agency level activities

Governments or agencies should perform QA on input data submissions to ensure the public of the accuracy of the submissions. Furthermore, government QC of the compilation process should be achieved. In addition, agencies can perform consistency checks by comparing gas usage information with independently acquired gas purchase records for the semiconductor industry and by checking the reasonableness of emission factors via confidential surveys with tool manufacturers. Finally, agencies should keep records of their QA/QC activities and publish annually FFC emissions from the semiconductor industry and the results of agency activities to assure quality.

4.3 External inventory QA/QC systems

Independent third parties, benchmarking groups or the public, under negotiated terms for handling confidential information could perform external review. Such efforts ensure that inventory methods are being followed consistently. Confidentiality barriers may be surmounted by both government and industry agreeing to third-party reviews or audits, under prescribed terms for accessing, examining, manipulating, reconciling differences and reporting the results of the review. In anticipation of such negotiations it should be recognized that many fabs are operated by multi-national corporations (i.e., single companies operate fabs in several countries) and that not all companies are members of all trade associations.

The adoption of a quality assurance/quality control system can ensure that the complex data-gathering, calculating and reporting processes that comprise inventory preparation produces an inventory in which all stakeholders have confidence.

5 CONCLUSIONS

Governments face several key challenges when developing inventories of FFC emissions from semiconductor manufacturing. The newness in FFC use as well as the exceptionally rapid growth rates, the geographical reach, and competitiveness of the semiconductor industry may appear at first to clash with the customary IPCC expectations for consistency, transparency, and third-party verifiability of country emissions. For example, the most recent *IPCC Guidelines* for estimating GHG emissions do not provide specific guidance on how to estimate

FFC emissions from semiconductor manufacturing. Furthermore, in the near term, the feasibility and cost-effectiveness of methods for continuously measuring FFC emissions in chemically complex factory waste streams seems doubtful. Nevertheless, FFC emissions may be estimated consistently at the factory level, using either simple or relatively sophisticated process mass-balance methods. Two broad methods are available. The first requires only specific-FFC gas purchase records. In this method, one assumes purchase equals usage equals emissions. The second method varies according to the available information about FFC emission factors, which account for FFC consumption during the process and which may be obtained from the owners of semiconductor manufacturing process technology. The simplest of the mass balances approaches uses, at the country level, an overall emissions factor averaged over all gases and processes together with country total FFC purchase records. The most sophisticated mass-balance approach employs gas- and process-specific emissions factors at the factory level together with specific gas usage records at the factory level. For any method, transparency and verifiability issues may be resolved by documenting the method used and through third-party audit procedures.

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