

# SF<sub>6</sub> FROM ELECTRICAL EQUIPMENT AND OTHER USES

## ACKNOWLEDGEMENTS

This paper was written by Jos G.J. Olivier and Joost Bakker (RIVM, The Netherlands). Jan Willem Wouda (Elin Holec, Amersfoort, the Netherlands), Rainer Bitsch (SIEMENS, Erlangen, Germany), Manfred Maiss (formerly at MPI, Mainz, Germany) and Dina Kruger (USEPA) reviewed it.

## ABSTRACT

The current consumption of sulphur hexafluoride (SF<sub>6</sub>) in electrical equipment is about 60% of which 42% is from original electrical equipment manufacturers and the remaining 18% goes to refill by electric utilities. For other uses the consumption is in the range of 11% to 34% which can be broken down as follows: truck tyres 2%, tennis balls, soles of sporting shoes 3%, soundproof windows 4%, miscellaneous applications labelled 'utilities' 23% and the remaining other applications 5%. In this paper, regional distribution and recent emission trends for 1990-1995 are discussed. Since 1995 there has been a distinct change in the trend due to the introduction in the market of new and quite different technology resulting in substantially less use of SF<sub>6</sub> per unit.

The default IPCC methodology for estimating SF<sub>6</sub> emissions - a Tiered approach - is reviewed. Tier 1A/1B uses apparent consumption, either using import/export amounts in bulk or in appliances, as emission estimate (also referred to as 'Potential emissions'). Tier 2 estimates actual emissions based on source-specific data. In the current *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC Guidelines)*, only default SF<sub>6</sub> emission factors are recommended for *Gas Insulated Switchgear (GIS) and circuit breakers* for the annual leakage component in phase 3 and disposal in phase 4. A summary is presented of presently available updated emission information as well as uncertainty estimates based on expert judgement. Regarding GIS and circuit breakers, results from a joint UNIPEDE/CAPIEL working group that has assessed the present situation within Europe are included.

Next, issues of completeness are discussed that relate to the type (tier) of the method selected for the estimation and to a large group of small applications that may be overlooked by inventory compilers. Then, present reporting guidelines on SF<sub>6</sub> sources and reporting practices are reviewed. In the Second National Communications, 18 Annex I countries (or about 50%) reported SF<sub>6</sub> emissions, which means that 17 other countries did not report SF<sub>6</sub> emissions at all. The latter may be due to incomplete knowledge of domestic sources or to unresolved confidentiality issues.

In case no reliable information on SF<sub>6</sub> use is available, a national survey of all possible sources could be made as a starting point for estimating national SF<sub>6</sub> emissions and monitoring of their trends. Governments may run into confidential business information issues, in which case an independent auditor may be required for monitoring (part of) the national emissions. This is likely to be the case if one wants to separately identify emissions from SF<sub>6</sub> producers, GIS manufacturers, or manufacturers of SF<sub>6</sub> containing sport attributes. Information from industry will be indispensable for compilation of proper default emission factors, time delay factors etc.

Subsequently, other source-specific issues on quality control and quality assurance (QA/QC) are discussed with respect to the (internal) verification and (external) validation of reported national SF<sub>6</sub> emissions. Validation of reported figures may benefit from public, peer and scientific review. Another way to validate aggregated emission results for large countries is comparison with regional emission estimates derived from local atmospheric measurements. The paper ends with recommendations on priority areas for improvement of methods, default emission factors, unidentified sources, and reporting guidelines in view of confidentiality issues.

# 1 INTRODUCTION

## 1.1 Nature, magnitude, distribution and trends of SF<sub>6</sub> sources

Emissions of SF<sub>6</sub> are virtually all of anthropogenic origin (Harnisch *et al.*, 1996). Estimation of global historical emissions of SF<sub>6</sub> can be based on a survey of global annual sales per application conducted by an independent auditor, Science and Policy Services (S & PS, 97). In this survey the following applications were distinguished as follows:

- *Electricity sector (separating Utilities and Equipment manufacturers)*, with applications in Gas Insulated Switchgear (GIS) and Circuit Breakers, while some others include gas-insulated high-voltage transmission lines and mini-stations; in addition 'Utilities' also includes the application of SF<sub>6</sub> in accelerators (for scientific and/or military purposes);
- *Magnesium industry* (primary production and die casting), with application as a cover gas in foundries for die casting to prevent oxidation of the molten magnesium;
- *Electronics industry*, where SF<sub>6</sub> is commonly used in semiconductor (chip waver) manufacturing processes for either plasma etching or as an etchant before chemical vapour deposition (CVD), and
- *Adiabatic property applications*, notably in tennis balls, shoe soles and in truck tyres;
- *Other applications*: gas-air tracer in research and leak detectors for medical purposes, electronic applications, soundproof windows, degassing aluminium specialties etc (for use as CFC/halon substitute – see IPCC Good Practice Background Paper 'Global emission sources of greenhouse gas emissions from industrial processes: SF<sub>6</sub>').

Furthermore, use in primary aluminium production to degas aluminium specialties occurred only during some years in the 90's (included in 'Other'). Finally, in addition to consumption, production of SF<sub>6</sub> also gives rise to some very small inadvertent emissions.

Historical global total emissions have recently been estimated by Maiss and Brenninkmeijer (1998) from the trend in historical atmospheric concentrations and matched with the results of the S & PS sales survey, combined with a few corrections for some periods. The authors noted a marked difference between the electrical equipment market in North America versus Europe and Japan and concluded that part of the consumption attributed to the electrical utilities could be used for other applications, possibly in the magnesium industry such as utilities that also own magnesium production facilities.

In a subsequent effort to reproduce the historical emission trends, Maiss and Brenninkmeijer (1998) from a 'bottom-up' analysis of national activities, and Olivier and Bakker (1999) made an estimate of global and national use and emissions of SF<sub>6</sub> per source category. They assumed that historical emissions per application up to 1995 follow the same pattern as consumption per application, except for Original Equipment Manufacturers (OEM), where emissions are 28% (USA), 30% prior to 1990 and 12% since 1995 (Europe), 35% (Japan) and 50% (other) of annual consumption, and soundproof windows where emissions from manufacturing are 33% and subsequent leakage is 1% annually. Emissions of truck tyres and sport attributes are assumed to have a three-year delay. Olivier and Bakker (1999) estimated global total SF<sub>6</sub> consumption as 8,250 tonnes and total resulting SF<sub>6</sub> emissions at 6,060 tonnes or 73% of annual consumption in 1995, which is in good agreement with atmospheric observations. These emissions are about 0.4% of present global total CO<sub>2</sub>-equivalent emissions and 12% of total industrial process emissions. Resulting emissions per SF<sub>6</sub> application are shown in Figure 1, which illustrates that electrical equipment emissions account for about half of the total SF<sub>6</sub> emissions.

## 1.2 Emission sources and trends for electrical equipment and other uses

Within the 'Electrical Equipment Sector' (equipment manufacturers and utilities) one can distinguish four phases of SF<sub>6</sub> use which are sources of emissions:

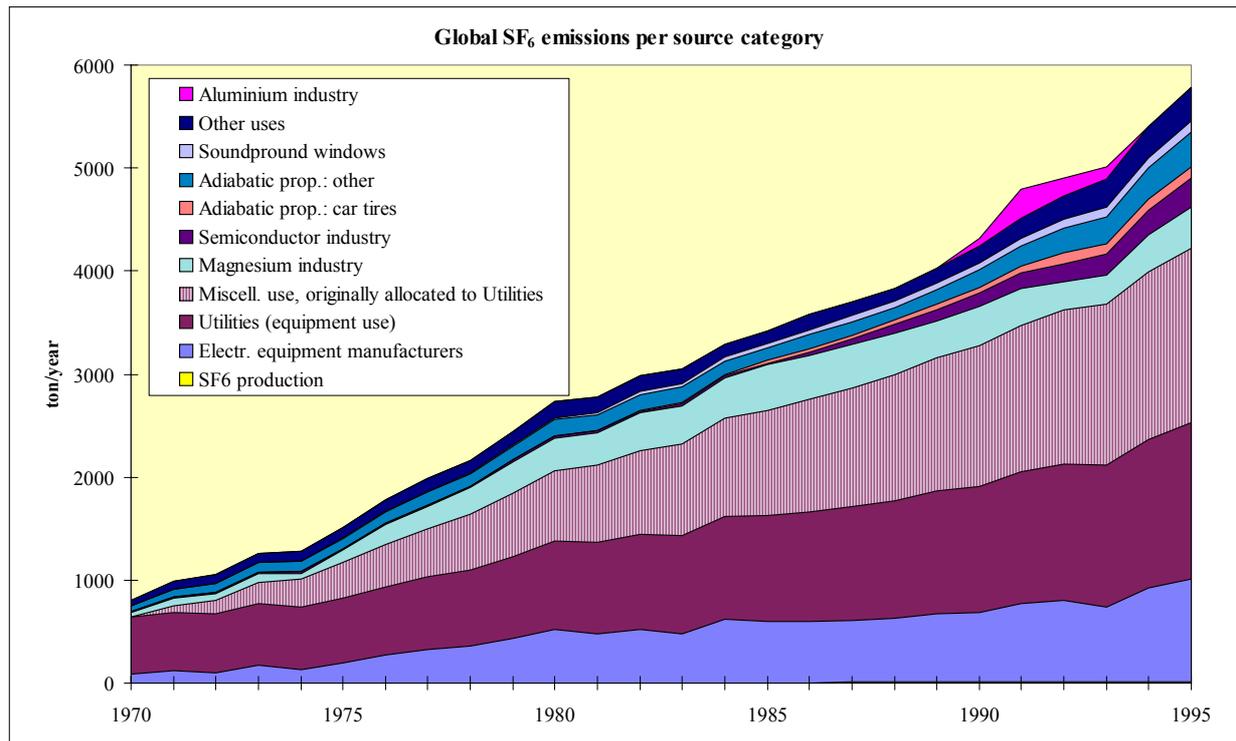
- Production in equipment plant (testing by manufacturers);
- Erection on site (commissioning by manufacturer, or utility);

- Usage by utilities (leakage, maintenance, stock refill), and
- Disposal by utilities (venting or, partial, recovery).

SF<sub>6</sub> containing electrical equipment is mostly *Gas Insulated Switchgear* (GIS). Often this GIS application accounts for more than 90% of SF<sub>6</sub> use for electrical equipment, except for North America where mostly (>90%) circuit breakers/dead tank equipment have been in use since the early 1960s. *GIS equipment manufacturing* started in the 1970s, with concentrations in Western European countries and Japan, whereas manufacturing of other electrical applications such as circuit breakers is spread over more countries. So-called dead tank switchgear is mostly manufactured - and used - in the USA. GIS equipment has a lifetime of about 30 years.

In the *utility sector*, GIS applications are predominantly used in Europe, Japan, Middle East and East Asia. However, SF<sub>6</sub> containing circuit breakers, the so-called dead tanks, are mostly used in the USA and Canada.

**Figure 1 Global historical SF<sub>6</sub> emissions by end-use categories**



The Other Uses (not discussed in other IPCC Good Practice Background Papers) consist of:

#### Utilisation of adiabatic properties (very low diffusion coefficient)

Examples are SF<sub>6</sub> in truck tyres, tennis balls, and sporting shoes. Emissions occur (a) at the manufacturing facility during handling and filling and (b) when disposed of at the end of its lifetime of about three years. Emissions from tyres are therefore assumed to have a three-year delay.

#### Soundproof windows

This application has three phases: (i) manufacture emissions (handling/filling), (ii) subsequent leakage, and (iii) disposal at the end of its lifetime of about 25 years.

#### Miscellaneous applications via purchase to utilities

Part of this could be (a) scientific applications, (b) military applications, (c) additional refill of utility equipment, or (d) additional consumption for magnesium production (may be the largest part according to Maiss and Brenninkmeijer (1998)).

#### Remaining other applications

This is a rather diffuse group of sources ranging from gas-air tracers to medical applications and aluminium degassing.

Sport attributes will probably be predominantly used in OECD countries, whereas SF<sub>6</sub> use in truck tyres and soundproof windows occur only in Germany (and some in neighbouring countries). Olivier and Bakker (1999),

using a kind of a ‘reference approach’ estimated a global total (1995) SF<sub>6</sub> consumption of 8,350 tonnes, and found the following division of consumption over the source categories ‘Electrical equipment’ and ‘Other uses’:

#### Electrical equipment (60%)

- Original electrical equipment manufacturers: 3,500 tonnes (42%), which is distributed as follows: 140 tonnes - USA, 1,200 tonnes - Europe, 1,400 tonnes - Japan, 500 tonnes - Russia, and 350 tonnes - China;
- Refill by electricity utilities: 1,500 tonnes (18%), of which 700 tonnes is in the USA and 400 and 370 tonnes from equipment made by European and Japanese manufacturers respectively (from a total stock of 3,500, 11,000 and 10,600 tonnes, respectively).

#### Other uses (11%, at maximum 34%)

- Truck tyres: 140 tonnes (2%), allocated to Germany;
- Tennis balls, soles of sporting shoes: 220 tonnes (3%), of which about 110 tonnes and 70 tonnes are for USA and Japan;
- Soundproof windows: 270 tonnes (4%), with a total of 1,700 tonnes in stock, predominantly in Germany;
- Miscellaneous applications labelled ‘Utilities’, either for accelerators or any other application: 1,700 ± 600 tonnes (23%), of which 1,200 ± 400 tonnes is for USA and 500 ± 200 tonnes for Europe;
- Remaining other applications: 340 tonnes (5%), of which about 90 tonnes are for USA, 50 tonnes in Japan and 25 tonnes in Germany.

Recent global growth trends 1990-1995 show an increase in emissions of 1,500 tonnes (+34%). As per application, the 1990-1995 trend is as follows (in tonnes, including Russia and China):

#### Electrical equipment

- Equipment manufacturers: 300 (+50%)
- Electricity sector: 300 (+25%) (estimated, after correction for miscellaneous)

#### Other uses

- Adiabatic properties: truck tires: 50 (+90%)
- Adiabatic properties: other: 150 (+100%)
- Soundproof windows: 50 (+60%)
- Remaining other use: 150 (+100%)
- Aluminium industry: -50 (-100%)

#### Miscellaneous

- Unknown, possibly magnesium: 350 tonnes (+25% (estimated)).

Although the electronics industry showed the largest growth rates, the electrical equipment manufacturers was the dominating consumption sector with 5-year growth rates of about 50%. However, since 1995 there has been a distinct change in the trend due to the market introduction of new and quite different technology (e.g. using 50% lower pressures), resulting in substantially less use of SF<sub>6</sub> per unit.

## 1.3 State of inventory methodology

The current IPCC default methodology for SF<sub>6</sub> emissions consists of a Tiered approach, ranging from relatively simple to rather detailed approaches:

- **Tier 1A and 1B**, consisting of *apparent consumption*, either using import/export amounts in *bulk* or in *appliances*, respectively. This is also referred to as ‘Potential emissions’, and
- **Tier 2**, which estimates the actual emissions based on source-specific activity data and emission factors.

Most inventories recently submitted by Annex I countries as part of their Second National Communications (26 out of 34) did not explicitly include actual emissions of SF<sub>6</sub> (UNFCCC, 1998).

## 2 METHODOLOGICAL ISSUES

### 2.1 Selection of *Good Practice* methods

The *IPCC Guidelines* (IPCC, 1997) describe a default methodology for SF<sub>6</sub> consisting of a Tiered approach. Tier 1A/1B uses apparent consumption, either using import/export amounts in bulk or in appliances, also referred to as ‘Potential emissions’ and in Tier 2 the actual emissions are estimated based on source-specific data. From the previous section, it is clear that within the *Electrical Equipment Sector*, the amounts of SF<sub>6</sub> consumed are in general not equal to emissions. For import/export of electrical equipment there will be no difference between Tier 1A and 1B since the SF<sub>6</sub> is shipped in separate containers, not as a component of a product. However, this may not be the case for the *Other uses* when countries export or import SF<sub>6</sub> containing products such as soundproof windows or tennis balls. In the latter case, the more detailed Tier 2 method will provide a much more accurate *national* emissions estimate than the Tier 1A or 1B approaches. Tier 2 will also provide a much more accurate estimate of actual annual emissions than the Tier 1 approach.

Therefore countries striving for a correct allocation of national emissions as well as estimating *actual* rather than *potential* emissions will apply the Tier 2 approach, since the two approaches can be very different. When using the Tier 2 approach one may wish to distinguish four phases of SF<sub>6</sub> usage within the large electrical equipment sector (equipment manufacturers and utilities):

- Production in equipment plant (manufacturers): handling, filling/testing, recovery;
- Erection on site (commissioning by manufacturer or utility): handling, filling;
- Usage by utilities: leakage, handling, refill of leakage, maintenance/venting, and
- Disposal by utilities: venting or recovery.

Making this distinction is also required so as to enable comparisons between countries and other validations with other reference data sets and with “top-down” emission estimates.

Analyses by Maiss and Brenninkmeijer (1998) and by Olivier and Bakker (1999) suggest that in most cases a fair estimate of global annual emissions from equipment in use can be made. This estimate is in agreement with atmospheric observations. This could be based on estimates per type of equipment (GIS, circuit breakers, etc.) by the industry of (a) total amount consumed at the equipment plant; (b) the total amount of stock in national equipment; (c) the amount annually purchased for refill (= compensation for leakage and maintenance losses), and (d) information on SF<sub>6</sub> use in newly installed equipment. In case the contribution is considered to be relatively large, a special survey could be conducted to get accurate activity data for the sector.

Currently, in OECD countries, about 25% of global total SF<sub>6</sub> emissions cannot be properly allocated to one of the main source categories (the ‘miscellaneous’ purchases to utilities). Therefore it could be recommended that countries carry out one basic survey of all national sources of SF<sub>6</sub> emissions that can subsequently be used for monitoring of activity data, emission factors and other relevant variables.

### 2.2 Emission factors

In principle, countries have three options for selecting emission factors for electrical equipment and other uses:

- IPCC default factors recommended in the *IPCC Guidelines*;
- Updated global or regional factors e.g. compiled by industrial or scientific organisations, and
- Nationally developed emission factors.

In practice, the situation is more complex, because for the *Electrical Equipment Sector*. *IPCC Guidelines* only cover leakage emissions from already installed equipment. The *IPCC Guidelines* do not provide recommendations for the maintenance emissions as well as for emissions in the equipment manufacturing plant and during erection of new newly installed equipment on site. Alternatively, countries may therefore wish to use *updated* global or regional default emission factors compiled by industry organisations (e.g. CAPIEL/UNIPEDE, 1999) based on recent assessments of information available within the industry.

For the ‘**Other Uses**’ the *IPCC Guidelines* do not provide recommendations for the specific applications that have a distinct delayed emission profile. In the case of truck tyres and *soundproof windows*, the individual country that utilises these applications (Germany) has developed country-specific emission factors. For other

**adiabatic property utilisation** like in sport attributes, no specific method – be it national or global – exists to date, but a delay of 3 years similar to truck tyres could be used.

In summary, if countries do not have representative country-specific information on emission factors, delay factors etc., they could either use *current* default values as recommended by the *IPCC Guidelines* or *updated* global/regional default emission factors such as more recent information compiled by industry organisations (e.g. CAPIEL/UNIPED, 1999, for emissions from the electricity sector). These values should preferably be based on a compilation of a consistent set of factors derived from global and regional information which has been checked for possible bias by a ‘top-down’ versus ‘bottom-up’ comparison of global annual emissions (i.e. concentration derived emissions versus per source/region/country estimated emissions).

For the *remaining other applications* a semi-prompt emission calculation of annual emissions, e.g. as described by Maiss and Brenninkmeijer (1998) and by Olivier and Bakker (1999), respectively, taking into account some delay between purchase and actual use of 6 months may be recommended. This is similar to approaches generally used in scientific models for calculating emissions of ozone depleting substances (Midgley and Fisher, 1999) and the time delay that was concluded by Maiss and Brenninkmeijer (1998) when fitting the adjusted S & PS data against the observed atmospheric concentrations.

We will now proceed in the way of summarising the *IPCC Guidelines* and other more recent emission factors data.

### 2.2.1 Current default emission factors

The *IPCC Guidelines* recommend the following default emission factors for SF<sub>6</sub>:

- (a) Fugitive emissions: not considered for SF<sub>6</sub>. However, for HFC and PFC, a default of 0.5% of total production of the compound is recommended, based on the default rate used for fluorocarbon processes (UNEP, 1994);
- (b) GIS and circuit breakers: each year 1% of the total quantity contained plus 70% (or to be precise: 74%) of the quantity of equipment manufactured in year t-30 (assuming a lifetime of 30 years and release upon disposal) (NILU, 1993). Also, the *IPCC Guidelines* note that ‘If data on total stock of GIS are unavailable, then it should be assumed that emissions equal consumption.’;
- (c) Fire suppression and explosion protection: Some of the new substitutes for halon in fire extinguishing equipment contain SF<sub>6</sub>, probably in blends with HFC. If products contain SF<sub>6</sub>, it is emitted in the same manner as HFC or PFC. Defaults for these emissions for mature markets are recommended as: 60% of the total quantity should be used in new portable equipment and 35% of the total quantity in new fixed (flooding) equipment. This is based on halon emissions from these types of applications (McCulloch, 1992). The *IPCC Guidelines* recommend that SF<sub>6</sub> emissions are calculated according to the proportion of SF<sub>6</sub> in the blend, and
- (d) Other applications: neither method nor defaults are given.

### 2.2.2 Currently available updated emission factor data

We will now briefly review the currently available emission factor data to be applied for SF<sub>6</sub> from production, electrical equipment and other uses.

- **For fugitive emissions from production:** UNEP (1994) mentions a range of 0.1-1.0% for CFC production and 0.5% for well-designed and well-managed facilities. For the production of carbon tetrachloride (CTC), a survey by European, US and Japanese manufacturers indicated an emission rate of 0.1%. This number is consistent with the production of a liquid, rather than a low boiling point gas (like CFCs) (UNEP, 1994). Contacts with manufacturers suggested that for inadvertent losses during production, an SF<sub>6</sub> default emission factor of 0.1% of total production could be recommended.
- **GIS and circuit breakers:** Initiatives from industry were started some years ago. In particular, a joint UNIPED/CAPIEL working group (UNIPED/CAPIEL, 1998) assessed the present situation within Europe. It concluded that in 1995 about 4 100 tonnes of SF<sub>6</sub> were installed in high-voltage switchgear in Europe (almost all GIS and predominantly in Western Europe) and that about 1 200 tonnes were purchased in 1995 by GIS manufacturers for use in new switchgear - included for export outside the EU. At present within the EU, filling and handling emissions during manufacturing in the factory and on-site during erection and commissioning are estimated at 12% of the total amount purchased by the manufacturers. According to CAPIEL/UNIPED (1999), about half of this 12% is emitted during manufacturing and the other half is emitted on site. Based on a comprehensive enquiry it is estimated that total emission from GIS equipment in service due to leakage and maintenance is about 3% of the 4 100 tonnes installed. For the

newest equipment, leakage rates only (i.e. excluding maintenance losses) are of the order of 0.5% per year. According to the industrial standard IEC 694 (IEC, 1996), equipment manufactured before 1980 has a maximum leakage rate of 3% and for newer equipment this value is 1%.

A Technical Committee of ETRA has examined the present situation in Japan (Takuma, pers. comm., 1998) and concluded from a survey that GIS manufacturing, erection and commissioning emissions in Japan in the period 1990-1995 were about 40% of the total amount of SF<sub>6</sub> purchased by the manufacturers. On-site measurements showed that the leakage rate is below 0.1% per year. In addition, there are emissions during maintenance (inspection), replacement and withdrawal. During maintenance current practice is that overall 60% of the SF<sub>6</sub> is recovered (70% of GIS > 100 kV and 0% of GIS < 100 kV). At present total stock emissions are estimated at about 1% of total installed stock of 6 200 tonnes in 1995. In addition, in Japan about 400 tonnes was used in 1995 for *insulating high-voltage cables* (Maiss and Brenninkmeijer, 1998). At present no emission factor data for this application exists.

When disposing of phased out GIS, industry recommendations (e.g. IEC 61634 and CIGRE SC 23) provide guidelines for handling, recycling and reuse of SF<sub>6</sub> aiming at maximum recovery. However, since GIS equipment has a lifetime of about 30 years and was introduced in the early '70s, under normal circumstances disposal of outdated equipment has not yet occurred.

- **For the USA**, the market is dominated mostly by *circuit breakers*. According to NEMA, in 1995 switchgear manufacturers purchased 140 tonnes of SF<sub>6</sub>, of which 28.5% was estimated to be emitted during manufacturing, erection and commissioning (NEMA, 1997). Annual refill and leakage compensation in the USA was estimated to be 20% of a total installed stock of 3 500 tonnes in 1995.
- For the **'Other applications'**, we have identified the following applications with a distinct different emission profile:
  - (a) **Adiabatic property applications:** for tyres a delay in emissions of 3 years is assumed; for other applications such as shoe soles and tennis balls, the same delay time may be used (Schwarz and Leisewitz, 1996);
  - (b) **Double glazing of soundproof windows:** it was assumed that 33% of the SF<sub>6</sub> was released, from the amount purchased, during fabrication (filling of the double glass window) and for the remaining stock contained inside the window an annual leakage rate of 1% of the stock is assumed for a period of 25 years. These assumptions in application in windows have been valid since 1975. For all other applications, a delay of one year is assumed, i.e. 50% is emitted in the same year and 50% is emitted in the year after the sale (Schwarz and Leisewitz, 1996), and
  - (c) **Fire suppression and explosion protection:** 60% of the total quantity is used in new portable equipment and 35% of the total quantity in new fixed (flooding) equipment, based on halon emissions from these type of applications (McCulloch, 1992).

Thus, for all *other* applications (except for magnesium production and use in the semiconductor industry) such as tracer, for medical applications, etc., (similar to halocarbon emission calculations), an average delay of one year may be assumed, i.e. 50% is emitted in the same year and 50% is emitted in the year after the sale. This leaves the question of where and how to estimate specific use in military applications and for accelerators. If no information is available, these could be dealt with as with the remaining 'other' applications (as semi-prompt emissions).

As shown by Maiss and Brenninkmeijer (1998), within their reconstruction of global SF<sub>6</sub> use and emissions, an average emission rate of about 30% from manufacturers is required to reproduce the atmospheric build-up of SF<sub>6</sub> concentrations until 1995. In parallel with the study of Maiss and Brenninkmeijer (1998) and of UNIPED/CAPIEL, Bitsch has estimated total stock in GIS and other electrical equipment in 1995 for different world regions (Bitsch, pers. comm., 1998). This information, as well as regional consumption estimates by major SF<sub>6</sub> manufacturers and the subsequent analysis carried out by Maiss, has been used by Olivier and Bakker to reconstruct the annual emissions from the electricity sector. They calculated the estimated total stock in electrical equipment in the USA, Europe and Japan at about 3 500, 4 100 and 6 200 tonnes of SF<sub>6</sub> respectively (about 12 000 and 10 000 tonnes for Europe and Japan, including exported equipment). For total manufacturing, erection/commission emission rates for 1970-1995 were 30%, 35% and 50% for European, Japanese and other equipment manufacturers, respectively, whereas for the USA 55% was used for years up to 1970 and decreasing to 29% in 1995. As for the leakage/maintenance rates the following set appeared to be consistent with both stock assumptions in 1995 and required emission trends: 20% for equipment in the USA (consisting mostly of circuit breakers, dead tank type), and 5% for equipment manufacturers prior to 1980 and 3% from 1980 onwards. An additional assumption was that 100% of the annual consumption in the USA and Europe of about 1200 and 500 tonnes, which is not accounted for in the utility sector (the 'miscellaneous' part), is emitted promptly. If part of

these quantities would be used for stock building, then the emission rates for leakage/maintenance would have to be somewhat higher.

Noting that the present *IPCC Guidelines* do not provide default factors for all source categories, countries may wish to use emission factors and other parameters described above since this data is more recent. These also have the advantage that they are in accordance with regional practices and in agreement with observed global total emission trends for all sources. Specific national factors, when not available, could be developed building on experience from other countries or industry organisations.

## 2.3 Activity data

Tier 1A activity data requires only aggregate data on national production and import and export in bulk. This information will, in principle, be available at either the producer or in customs administrations though individual elements may be considered confidential business information. However, Tier 1B also requires keeping track of import and export of SF<sub>6</sub> containing products, which is a much more elaborate effort to compile. For the parts of 'other uses' one may wonder whether this is a cost-effective approach compared to the relative minor part of the national inventory that we are dealing with here.

When using the Tier 2 approach, the activity data – on which emission calculations are based – are mostly national SF<sub>6</sub> consumption figures per subcategory. In case no reliable information on this matter is available for all possibly significant sources of SF<sub>6</sub>, a national survey of all possible sources could be made as a starting point for estimating national SF<sub>6</sub> emissions and monitoring trends in them. This is particularly useful in cases where information from different sources does not lead to conclusive national consumption figures as well as when unknown amounts of SF<sub>6</sub> are imported or exported in products of which the size of the flows across the borders are not or not well monitored (e.g. sporting equipment, windows, tyres).

## 2.4 Uncertainty

In this section we intend to compile a draft set of default uncertainty ranges so as for the emission factors to have a concrete proposal for discussion among the experts. These have been selected from the following list of ranges, which are classified by a more or less fixed order-of-magnitude difference between subsequent values (Table 1):

Uncertainty (%)	Uncertainty factor (-)	Qualitative uncertainty
± 5	1.05	very small
± 10	1.10	small
± 25	1.25	medium
± 50	1.50	large
± 100	2.00	very large
± 200	3.00	extremely large

According to the Annex I of the Reporting Instructions in the *IPCC Guidelines*, the uncertainty percentages should be interpreted as providing  $2\sigma$  (standard deviation). In the case of a Gaussian distribution  $2\sigma$  corresponds with a 95% confidence interval. Note that in cases where the uncertainty is estimated to be more than  $\pm 50\%$ , the interpretation of the lower percentage band of the range is not meaningful. As with the smaller uncertainties, this should be interpreted as the corresponding uncertainty factors: an uncertainty range between minimum value (value/factor) and maximum value.

From the preceding discussion on recent information, the following conclusions have been tentatively drawn regarding uncertainty ranges of emission factors, using expert judgement of the underlying data sources:

- SF<sub>6</sub> production: default emission factor 0.1% of total production - uncertainty range 50%.
- GIS manufacturing, site erection and commissioning:
  - European manufacturers:
    - prior to 1995: 30% - uncertainty range 10%;

- from 1998 onwards: 12%, of which about 1/2 is emitted during manufacturing and 1/2 on site (for each of the 6% - uncertainty range 25%).

Japanese manufacturers:

- prior to 1995: 35% - uncertainty range 10%;
- from 1998 onwards 12% - uncertainty range 25%

- GIS leakage plus maintenance:
- European GIS, total:
  - equipment manufactured before 1980: 5% - uncertainty range 25%;
  - newer equipment: 3% - uncertainty range 25%.

Japanese GIS, total:

- equipment manufactured before 1980: 5% - uncertainty range 25%;
- newer equipment: 1% - uncertainty range 50%.

All cases include leakage rates:

- of equipment manufactured before 1980: 3% - uncertainty range 50%;
- of newer equipment: 0.5% - uncertainty range 100%.

- *Circuit breakers manufacturing*, site erection and commissioning:
  - 55% for years up to 1970, decreasing to 29% in 1995 - uncertainty range 50%.
- Circuit breaker leakage plus maintenance:
  - 20% of a total installed stock - uncertainty range 50%.
- *Insulation of high-voltage transmission lines*:
  - default and uncertainty range unknown.
- Adiabatic property applications:
  - for tyres: delay of 3 years - uncertainty range 25%;
  - for other applications: delay of 3 years - uncertainty range 100%.
- Double glazing of soundproof windows:
  - release during fabrication (filling of the double glass window) 33% - uncertainty range 25%;
  - annual leakage rate of 1% - uncertainty range 50%.
- For all other applications: delay of 1 year - uncertainty range 50%
- Fire suppression and explosion protection:
  - 60% of the total quantity used in new portable equipment - uncertainty range 25%;
  - 35% of the total quantity used in new fixed equipment - uncertainty range 25%.

Regarding the uncertainty in national activity data, the following observations can be made:

- Since SF<sub>6</sub> is a compound whose physical amounts purchased and used can be well measured, companies should be able to have a good bookkeeping of incoming and outgoing amounts of SF<sub>6</sub>;
- At the national level there are only a limited number of equipment manufacturers and electrical utilities, which form a well-defined group of users for which accurate activity data collection should be feasible, and
- The group of 'other' users may be more diffuse and thus it may be rather difficult to efficiently monitor the annual consumption. The major task is to monitor the uses in the distinct emission subcategories of (a) truck tyres; (b) other adiabatic properties (e.g., sport attributes); (c) soundproof windows; (d) remaining, semi-prompt, emission sources. However, if the delayed emission sources (a) to (c) occur in a country, the number of firms may be limited.

In conclusion, uncertainty ranges in activity level data may be small when a limited number of firms has to be surveyed; if this is not the case then uncertainties will be higher, but the relative contribution to the national inventory will be small.

## 2.5 Completeness

### 2.5.1 Consistent use of definitions

Since the '*Miscellaneous applications*' category may be composed of applications with prompt and with delayed emissions, it may be recommended that reporting of this category is subdivided into the category of prompt emissions and categories of delayed emissions, grouped according to their emissions profile. Specifying the most important applications per subcategory will assist in aggregating national reports of groups of countries and inter-comparison between countries. Military applications considered to be confidential could possibly be included into the subcategories mentioned above if they have similar emission characteristics.

When *GIS or other equipment* is manufactured in one country and installed in another, a clear definition of *national* emissions is essential. The GIS manufacturer may either fill the installation abroad himself or just ships the required SF<sub>6</sub> in containers along with the GIS in case the buyer does the erection and filling. However, in both cases the SF<sub>6</sub> is shipped separately and not in the product. Since Tier 1A and Tier 1B differ in that import/export in bulk or in appliances are accounted for differently, for GIS this will not result in different figures, but these flows across the borders should be included in the monitoring for a complete Tier 1 calculation.

A rather different situation is found in *adiabatic property utilisation* such as production, use and disposal of tennis balls and sport shoes containing SF<sub>6</sub>. Here, figures will be different for Tier 1A and 1B, and emissions during use and disposal can be in another country than where they were produced.

Finally, for completeness, one should also include emissions from *SF<sub>6</sub> production*, although emissions are in general assumed to be extremely small.

### 2.5.2 Meaning of the 'other' categories

In the *IPCC Guidelines* the following subcategories are dealt with explicitly:

- Magnesium gas covering and aluminium degassing;
- Fire extinguishing;
- Aerosols and solvents (as substitute for CFC applications), and
- GIS and circuit breakers.

All other miscellaneous sources are labelled as 'Other'. Compared to the S & PS survey, adiabatic property applications are not mentioned separately. However, these applications, as well as use for soundproof windows, and possibly accelerators and military applications are characterised by their delayed emissions. This is in contrast with the many applications mentioned in the literature as 'Other': gas-air tracer in research and leak detectors, medical purposes, electronic applications, degassing of aluminium specialties, discharge testing agent for fire suppression systems, etc. So it may be recommended that these subcategories of 'Other' with delayed emissions are reported separately or at least mentioned explicitly as being part of the list of sources occurring/not occurring in the country, including military applications.

### 2.5.3 Identification of additional end-uses

Within the electricity sector, the dominant use of SF<sub>6</sub> is:

- Mostly in circuit breakers (so-called dead tank equipment) in USA and Canada, and
- In GIS (over 95% of the sectoral use) in all other countries.

However, SF<sub>6</sub> has also been reported to be used in gas-insulated high-voltage transmission lines substations (mini-stations) and transformers. Since these applications may have quite distinctive emission determining features, it may be recommended that countries provide a clear description of what electrical equipment is included in the national emission inventory.

## 2.6 Other important issues

The assessment of the S & PS survey by Maiss and Brenninkmeijer (1998) showed that even on a global (regional) basis, complete sectoral reporting has not yet been achieved. About 60% of all SF<sub>6</sub> consumption is related to electrical equipment. When reporting of consumption data is done on a national basis, correct allocation into proper, homogeneous categories is highly recommended in order to have an option for a check of global total sectoral emissions against observed trends in concentrations (check for completeness and possible bias).

This means that consumption for accelerators and military applications should be reported separately from those of electrical equipment operated by utilities, and if the associated emissions are not (semi-)prompt emissions, they should be reported separately together with specific values for commissioning losses, operational losses and disposal losses.

It should be noted that the Tiers 1A and 1B are by definition not comparable in the sense that in specific circumstances the figures they produce may differ by an order of magnitude. The same remark can be made when comparing results of Tier 1 'potential' emission estimates with Tier 2 'actual' emissions calculations. Of the few countries that reported according to both definitions, the ratio between *actual* to *potential* was between 1:2 and 1:130 (UNFCCC, 1998).

## 3 REPORTING AND DOCUMENTATION

### 3.1 Current IPCC Guidelines

The *IPCC Guidelines* are used to guide countries in the preparation and submissions of annual greenhouse gas emissions inventories to the UNFCCC Secretariat. 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, major assumptions, methodological descriptions, and enough data to allow a third party to reconstruct the inventory from national activity data and assumptions, and
- An uncertainty assessment.

Countries *should* report SF<sub>6</sub> emissions from SF<sub>6</sub> production, Electrical equipment and Other uses under IPCC subcategory **2C4** (SF<sub>6</sub> used in Aluminium and Magnesium Foundries), **2E2** (Fugitive emissions) and **2F6** (Other consumption of SF<sub>6</sub> (please specify)), both as potential and actual emissions.

At present, the *IPCC Guidelines* do not ask for the splitting of the different emission sources of SF<sub>6</sub> of IPCC subcategory '2F6 Other (to be specified)' in the standard sectoral report ('Table 2'). It is *requested*, but not mandatory, that countries specify, in additional tables, the emissions reported under '2F6', e.g. the GIS and other switchgear equipment sector and the 'Other' sources, when applicable. As discussed above, different emission factors apply to these subcategories.

Unless the sources included are explicitly specified (or mentioned), it will be impossible to assess the completeness of this part of the inventory. In addition, the current level of detail of fixed format for reporting will not allow national teams to compare the emission factors used with those applied by other countries. Also it will not help to check the total SF<sub>6</sub> consumption emissions of the total group of countries for possible group bias by analysing the data set and comparing with atmospheric trends.

In the IPCC/UNFCCC reporting instructions the term 'national' emissions may not always be defined in an unambiguous way. One can question whether shipment of SF<sub>6</sub> containing tennis balls and shoes to foreign markets (import/export of products) can be properly accounted for, since these SF<sub>6</sub> containing products are likely not labelled as such nor registered at the border. When dealing with disposal emissions this could also be reported under IPCC category 6 (Waste). The guidelines should provide clear guidance in which country these emissions should be accounted for and under which category.

### 3.2 Current reporting practices; focus on Actual/Potential issues

We recall that Tiers 1A and 1B are by definition *not comparable* in the sense that in specific circumstances the figures they produce may differ by an order of magnitude. The same remark can be made when comparing results of Tier 1 'potential' emission estimates with Tier 2 'actual' emissions calculations. For example, of the

few countries that reported according to both definitions, the ratio between *actual* to *potential* was between 1:2 and 1:130 (UNFCCC, 1998).

Although the largest part of total SF<sub>6</sub> consumption is emitted (semi-)promptly in the same or the subsequent year, in particular in the EOM sector and in some sub-sectors of the 'Other uses' (adiabatic properties and soundproof windows), emissions have long delay times or could be for the largest part avoided when recovered at the end of the lifetime. While this is of less importance for the global total aggregate, for individual countries the difference between actual and potential emissions can easily be a few hundred percent. This means that for having *comparable* inventories, it will be required that all countries also estimate and report their actual emissions. Using reasonable (that is globally calibrated) regional emission factors should not pose too large a problem.

In the Second National Communications, 18 Annex I countries (or about 50%) reported SF<sub>6</sub> emissions, which means that 17 other countries did not report SF<sub>6</sub> emissions at all. Of these 18 countries only 3 reported both potential and actual emissions, 5 reported only potential, 5 reported only actual and the remaining 5 reported emissions but did not specify whether these are potential or actual emissions. In conclusion, most inventories recently submitted by Annex I countries as part of their Second National Communications (26 out of 34) do not explicitly include actual emissions of SF<sub>6</sub> (UNFCCC, 1998).

At present many countries do not report any SF<sub>6</sub> emissions, not even according to Tier 1A. Presumably these inventories are *not complete*. Also, countries who report SF<sub>6</sub> emissions often do not provide clear supporting information showing whether Tier 1A or 1B was used for reporting Potential emissions and whether Actual emissions indeed are perhaps still potential emissions. Thus *transparency* in the current reporting is quite low. This may be partially due to the fact that many Parties still reported their inventory in the Second National Communication on the basis of the (reporting format) of the *original IPCC Guidelines* instead of using the tables defined in the *IPCC Guidelines*.

### 3.3 Confidential business information

For the 'OEM' and 'Other uses' sectors, confidentiality of information on SF<sub>6</sub> is a real issue for quite a number of countries. If the *UNFCCC Guidelines* acknowledge this aspect and continue to allow for aggregate reporting in some cases (as the current practice), then the controversy with the requirement of transparency should be acknowledged as well. It seems that this is a generic, cross-cutting issue in UNFCCC inventories, which also shows up when reporting industrial emissions of other gases, for example N<sub>2</sub>O from adipic acid or from nitric acid manufacture.

Transparency, if required for relatively small sources of less than 1% in CO<sub>2</sub>-eq. (e.g. of the order of 0.2% for electrical equipment), will cause a number of countries to run into issues of *confidential business information* due to the limited number of companies within some sub-sectors. In particular in countries with one or only a few manufacturers of GIS or other major SF<sub>6</sub> containing appliances such as sport equipment, separate reporting SF<sub>6</sub> consumption or emissions from this subcategory may be prohibited by rules of confidentiality of industrial statistics. Also data concerning military activities may be considered confidential.

This could be circumvented by having an independent auditor who monitors national apparent consumption and actual emissions using a documented scheme of emission factors applied. The question here is, what is the importance of requiring to report at a lower level of detail so as to allow checking, at least partly, of the figures reported in this section of the national emission inventory and to facilitate checking on global sectoral totals. Also, filling in of the gap identified by Maiss and Brenninkmeijer (1998) may not be assisted by this very aggregated reporting format.

A simple check could be to firstly assess which level of confidence is required by manufacturers or military applications, and secondly to determine what level of reporting is feasible in terms of sub-sectors and providing both activity (consumption) data and meaningful sectoral emission factors. The latter would also allow checking comparability between countries and the default emission factors recommended in the *IPCC Guidelines*. Some GIS manufacturers already announced that they consider their net SF<sub>6</sub> consumption data as confidential.

In case confidentiality still prohibits reporting at some disaggregated level, then a solution may be to aggregate the sectors consumption and emission data within another larger category. Although transparency is not possible in these areas, inventories may still be trustworthy if these aggregated totals have been subjected to regular checks by an independent auditor.

## 4 INVENTORY QUALITY

## 4.1 Introduction

Monitoring and reporting of national emissions should be at a qualitatively sufficient level, in order to be confident that a country meets its reduction objectives. Other countries will be confident that this is the case when either the ‘National System’ for inventory compilation has built-in guarantees that *Good Practice Standards* (to be specified) have been applied or when the reported inventories can be verified (i.e. independently checked) to be *Comparable*, *Complete* and *Consistent*. This could be in the sense that other countries can either independently verify the national inventory itself or the quality of key elements of the compilation process (‘National System’). This is also referred to as *transparency* of the inventory: the construction process should be clearly explained; *documentation* is sufficient to be able to reconstruct it and clarifies major causes of emission trends. Also, this should enable independent external, public, stakeholder and scientific review. These requirements can be summarised as a QA/QC programme that should have two distinct components as mentioned in the IPCC Good Practice General Background Paper:

- **Quality Control (QC):** This is a system of routine technical activities, implemented by inventory development personnel to measure and control the quality of the inventory as it is being developed. Quality control activities include technical reviews, accuracy checks, and the use of approved standardised procedures for emission calculations. For each source, experts should determine which aspects most heavily influence the ultimate emissions estimate. It is on these sensitive aspects that QA/QC usually needs to be targeted.
- **Quality Assurance (QA):** These are activities that include a planned system of review and audit procedures conducted by personnel not actively involved in the inventory development process. The key is to have a review by an independent, objective third party to assess the effectiveness of the internal QC programme and the quality of the inventory, and to reduce or eliminate any inherent bias in the inventory processes. In essence, the QA programme ensures that the inventory QC process was correctly performed.

As mentioned in the *General Background Paper* application of *Good Practice Standards* for QA/QC, inventory preparation relates to the need for thorough *documentation* of the inventory process, emission results and reporting process that make them *transparent* and credible. An effective QA/QC programme will include planning, numerous QC checks during inventory development and QA audits at strategic points in the process.

## 4.2 Internal inventory QA/QC systems

For sources of SF<sub>6</sub>, a major decision is when a country will start to estimate actual emissions of SF<sub>6</sub> or that it limits its national reporting of this compound to estimates of potential emissions. If actual emissions are to be calculated, then the key question is, whether there is sufficient monitoring of relevant activities and whether the appropriate emission factors can be determined, in particular if IPCC defaults are judged to be not appropriate for national application. We recall that in cases when no reliable information on this matter is available, a national survey of all possible sources could be made as a starting point for estimating national SF<sub>6</sub> emissions and monitoring of trends in them. Here governments may also run into confidential business information issues, in which case an independent auditor may be required for monitoring (part of) the national emissions. This is likely to be the case if one wants to identify separately emissions from SF<sub>6</sub> producers, GIS manufacturers, or SF<sub>6</sub> containing tennis ball or sport shoe manufacturers, because quite often there are too few of these companies in a country so that sectoral aggregate data would sufficiently conceal confidential business information. So this issue is an important one to consider for SF<sub>6</sub> sources, be it the large electrical equipment sector or the various smaller sources included in the ‘Other’ category.

A key cross-cutting question for the sources of SF<sub>6</sub> is to what extent should the focus on inventory improvement be related to the present or expected share in total national CO<sub>2</sub>-eq. emissions (currently only about 0.4% globally). Alternatively, this could be addressed on a gas-by-gas basis, because otherwise improvement of monitoring of the ‘new’ gases would never get priority.

Besides a description of the National System for preparing national emission inventories, choices have to be made regarding selection of methodology (default or national) and emission factors (IPCC defaults, industry recommendations or local). In addition, there is the question of the level of effort to be put into data checking procedures (validation), level and type of review prior to release, documentation, possibilities of independent checks. Here one could take a cost-effective approach in prioritising this according to the relevance for national total greenhouse gas emissions or for the trends in them, or having different levels of detail in subsequent years.

Validation that emission factors applied for equipment manufacturers, utilities and other users are in line with those used by other countries (i.e. checking comparability) can be done only if all countries supply this information, so that weighted or unweighted group average factors can be determined.

### 4.3 External inventory QA/QC systems

At present, from the Second National Communications it appears that countries have their own specific procedures for data checking and review. For example, the USA has recently put up the draft update of their national greenhouse gas inventory on the Internet for public review. On the other hand, in the Netherlands the inventory preparation procedures focus on per source categories. Relevant experts from key research institutes are brought in so as to guarantee consensus on the best method and best data to calculate national emissions for the various sectors. Of course, both countries also carry out other activities to improve or validate the national inventory, but this example illustrates that present national systems may include fairly different approaches for inventory preparation and associated QA/QC activities.

Sources of SF<sub>6</sub>, information from industry are indispensable for compilation of proper default emission factors, time delay factors etc. However, because of the attention raised in recent years for the global warming potential of SF<sub>6</sub>, it can be expected that the SF<sub>6</sub> consuming industry is now in a transient period. Various literature sources indicate that the losses of SF<sub>6</sub> in different stages of the use of the compound will decrease. This may be partly due to autonomous developments (e.g. use of more compact systems), but these may be strengthened by the newly raised interest from the public and politicians. Validation of reported figures would certainly benefit from public, peer and scientific review.

Therefore determination of unbiased emission factors for the reference year 1995 and the preceding period, as well as for current years, can be a difficult task as required historical data may just not be available or considered confidential. On the other hand, the original equipment manufacturing industry in Europe and Japan are very active and co-operative in assisting in the construction of a consistent dataset of SF<sub>6</sub> sources in time. Public, scientific and industry review of inventories compiled in the field of SF<sub>6</sub> could therefore benefit from the input from various experts on aspects of the global SF<sub>6</sub> puzzle.

For large countries such as the USA or the EU another way to validate (i.e. independently check) aggregated emission results that are not transparent because of confidentiality issues is to compare with regional emission estimates derived from local atmospheric measurements (Bakwin *et al.*, 1994). This may give at least a check of the order of magnitude of the regional emissions.

For the new gases in particular, checking of *global total* reported emissions for a possible bias in the whole set of inventories is possible by comparison with global emissions inferred from atmospheric concentration measurements. For SF<sub>6</sub> this verification activity could be useful for identifying either that part of the sources not yet accounted for (overall completeness check) or that the aggregate of emission factors and their trends in time are biased (overall comparability and consistency check). However, if countries do not attempt to make accurate estimates of these emissions on the grounds that their relevance in the national total is minor, then these types of checks will not be feasible. Another way of external (or internal) checking completeness and for possible bias in emission estimates is by comparison with other reference data sets, e.g. those for fossil-fuel CO<sub>2</sub> of the IEA and those of other sources compiled by GEIA/EDGAR.

## 5 IDENTIFICATION OF PRIORITY AREAS

Looking back at the data sources used for compiling the *IPCC Guidelines*, the current practice in reporting SF<sub>6</sub> emissions to the UNFCCC Secretariat, and the recent global/regional assessment of historical SF<sub>6</sub> emissions by Maiss and Brenninkmeijer (1998) and others, the following priority areas may be recommended:

- Define the relative priority to be given to SF<sub>6</sub> sources, either as part of total CO<sub>2</sub>-eq. emissions (in which case they are almost non-relevant) or on a compound by compound basis (in which case the ranking within the group of SF<sub>6</sub> sources are important);
- Update of default emission factors for switchgear, distinguishing between GIS and circuit breakers, between manufacturing, handling, erection, use/maintenance, and disposal/recovery, and distinguishing between old and new equipment and, possibly, between world regions - in co-operation with the global and regional sectoral industry organisations;
- Investigation of the emission sources of the gaps identified for North America and, to a lesser extent, Europe; this will either introduce new sources to be monitored or result in adjustment of default emission factors or activity data of existing source categories;
- Defining and adding default emission and delay factors for application in truck tyres, sport equipment and soundproof windows to the *IPCC Guidelines*;
- More accurate definition of which emissions are to be considered part of the *national* total and under which *category* to report them (notably disposal emissions);

- Survey all other current uses and define the associated default emission factors as they are identified - e.g. for insulating high-voltage power cables in Japan, and
- Analyse how to monitor and report emissions from sectors where confidential business information prohibits transparent reporting of emissions; define the level at which this problem can be avoided and what additional requirements this puts on the national QA process.

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