

CHAPTER 7

EMISSIONS OF FLUORINATED SUBSTITUTES FOR OZONE DEPLETING SUBSTANCES

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7 EMISSIONS OF FLUORINATED SUBSTITUTES FOR OZONE DEPLETING SUBSTANCES

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

7.1 INTRODUCTION

7.1.1 Chemicals and relevant application areas covered

Hydrofluorocarbons (HFCs) and, to a very limited extent, perfluorocarbons (PFCs), are serving as alternatives to ozone depleting substances (ODS) being phased out under the Montreal Protocol. Current and expected application areas of HFCs and PFCs include (IPCC/TEAP, 2005 and UNEP-TEAP 2016a/b):

- refrigeration and air conditioning;
- fire suppression and explosion protection;
- aerosols;
- solvent cleaning;
- foam blowing; and
- other applications¹.

These major groupings of current and expected usage are referred to in this chapter as *applications* within the ODS substitutes category. This introduction (Section 7.1) provides a general framework for estimating emissions from ODS substitutes, and subsequent sections (Sections 7.2 through 7.7) provide more specialised guidance on the individual applications introduced above. Some of these applications themselves encompass products or uses with diverse emission characteristics, and countries will produce more rigorous estimates if they account for this diversity through the adoption of disaggregated assessments (higher tier). Additionally, the use of HFCs and PFCs in some applications, specifically rigid foam (typically closed-cell foam), refrigeration and fire suppression, can lead to the development of long-lived *banks*² of material. The emission patterns from these uses can be particularly complex and methods employing disaggregated data sets are essential to generate accurate emissions estimates. Other applications, such as aerosols and solvent cleaning may have short-term inventories of stock but, in the context of emission estimation, can still be considered as sources of prompt emission. This statement also applies to flexible foams (typically open-cell foam).

HFCs are chemicals containing only hydrogen, carbon, and fluorine. Prior to the Montreal Protocol and the phase-out of various ODS, the only HFCs produced were HFC-152a, which is a component of the refrigerant blend R-500, and HFC-23, a low temperature refrigerant which is a by-product of HCFC-22³ production. HFC-134a entered production in 1991 and a variety of other HFCs have since been introduced and are now being used as ODS substitutes (IPCC/TEAP, 2005) among other applications. When collecting data on HFC and PFC consumption for reporting purposes, care needs to be taken to include those HFCs in blends, but, at the same time, to avoid including those components of a blend which are not required to be reported (e.g., CFCs and HCFCs).

HFCs and PFCs have high global warming potentials (GWPs) and, in the case of PFCs, long atmospheric residence times. Table 7.1 gives an overview of the most important HFCs and PFCs, including their main

¹ HFCs and PFCs may also be used as ODS substitutes in sterilisation equipment, for tobacco expansion applications, and as solvents in the manufacture of adhesives, coating and inks.

² A bank is in this context the amount of ODS-substitutes stored in products (applications) in a country.

³ HCFCs - hydrochlorofluorocarbons.

application areas. The various HFCs and PFCs have very different potencies as greenhouse gases. PFCs have particularly high GWPs regardless of the integrated time horizon adopted because of their long atmospheric lifetimes. The consumption patterns relating to individual gases must be known, therefore, or estimated with reasonable accuracy, to achieve useful assessments for the contribution to global warming from emissions of these groups of chemicals.

As CFCs, halons, carbon tetrachloride, methyl chloroform, and, ultimately, HCFCs are being finally phased out⁴, HFCs are being selectively used as replacements. PFCs are also being used, but only to a limited extent. HFC use is expected to continue to grow, at least in the short term (UNEP-TEAP, 2016a/b).

Since the 2006 IPCC Guidelines were finalized, a major change has occurred in the policy framework regulating HFCs. Formerly, HFCs, which do not directly deplete O₃, were not regulated under the Montreal Protocol. However, during the 28th meeting of the parties (MOP28) held in Kigali (Rwanda) in October 2016, 197 countries adopted an amendment to phase down HFCs. The parties committed to cut the GWP-weighted production and consumption of HFCs by more than 80 percent over the next 30 years. Developed countries will begin reducing HFC consumption in 2019 and developing countries will follow with a freeze of HFC consumption levels between 2024 and 2028. A small group including the world's hottest countries (India, Pakistan, Iran, Saudi Arabia and Kuwait) will freeze HFC use by 2028. These production and consumption limits are expected to drive changes in the quantities and types of HFCs used in ODS substitute applications. To ensure that their HFC emissions inventories remain accurate, inventory compilers should familiarize themselves with the HFC limits in their countries and plan to gather data on the associated changes in HFC use and emissions.

TABLE 7.1 (UPDATED)
MAIN APPLICATION AREAS FOR HFCs AND PFCs AS ODS SUBSTITUTES¹

Chemical	Refrigeration and Air Conditioning	Fire Suppression and Explosion Protection	Aerosols		Solvent Cleaning	Foam Blowing	Other Applications ²
			Propellants	Solvents			
HFC-23	X	X					
HFC-32	X						
HFC-125	X	X					
HFC-134a	X	X	X			X	X
HFC-143a	X						
HFC-152a	X		X			X	
HFC-227ea	X	X	X			X	X
HFC-236fa	X	X					
HFC-245fa	X			X		X	
HFC-365mfc				X	X	X	
HFC-43-10mee				X	X		
PFC-14 ³ (CF ₄)		X					
PFC-116 (C ₂ F ₆)							X
PFC-218 (C ₃ F ₈)							
PFC-31-10 (C ₄ F ₁₀)		X					
PFC-51-14 ⁴ (C ₆ F ₁₄)					X		

⁴ Refer to <http://hq.unep.org/ozone/> for the phaseout schedules dictated under the Montreal Protocol.

TABLE 7.1 (UPDATED) (CONTINUED)
MAIN APPLICATION AREAS FOR HFCs AND PFCs AS ODS SUBSTITUTES¹

Source: IPCC (1996), IPCC (2001), IPCC/TEAP (2005), UNEP-TEAP (2016a)

¹ Several applications use HFCs and PFCs as components of blends. The other components of these blends are sometimes ODSs and/or non-greenhouse gases. Several HFCs, PFCs and blends are sold under various trade names; only generic designations are used in this chapter.

² Other applications include sterilisation equipment, tobacco expansion applications, plasma etching of electronic chips (PFC-116) and as solvents in the manufacture of adhesive coatings and inks (Kroeze, 1995; U.S. EPA, 1992a). Note that although the use of PFCs for plasma etching is mentioned as an example in footnotes 2 and 3 to this table, the methodology for estimating emissions is described in Chapter 6 of Volume 3: Electronics Industry Emissions.

³ PFC-14 (chemically CF₄) is used as a minor component of a proprietary blend. Its main use is for semiconductor etching.

⁴ PFC-51-14 is an inert material, which has little or nil ability to dissolve soils. It can be used as a carrier for other solvents or to dissolve and deposit disk drive lubricants. PFCs are also used to test that sealed components are hermetically sealed.

7.1.2 General methodological issues for all ODS substitute applications

7.1.2.1 OVERVIEW OF ODS SUBSTITUTE ISSUES

No refinement.

7.1.2.2 CHOICE OF METHOD

As already described, emissions of ODS substitutes can be estimated in a variety of ways with varying degrees of complexity and data intensity. This chapter provides less data-intensive Tier 1 methods, typically based on low levels of disaggregation, and more data-intensive Tier 2 methods, which require higher levels of disaggregation. A third Tier (Tier 3), based on actual monitoring and measurement of emissions from point sources, is technically possible for specific sub-applications but this is rarely, if ever, employed for ODS substitutes, because the individual point sources are widely disparate. Accordingly, Tier 3 methods are not addressed further in this chapter.

TIER 1 METHODS

Tier 1 methods tend to be less data-intensive and less complex than Tier 2 because emission estimates are usually carried out at the application level rather than for individual products or equipment types. However, the approaches proposed vary considerably depending on the characteristics of the specific application. There can be Tier 1a approaches, Tier 1b approaches and, sometimes, combinations of the two (Tier 1 a/b). The latter is often the case where data are in short supply. Effectively, the output of a Tier 1a approach can be cross-checked using a Tier 1b method. In general, however, the simple methods tend to be based primarily on a Tier 1a approach (emission-factor approach) with the default emission factor being up to 100 percent for prompt release applications.

For simpler Tier 1 approaches, the chemical sales data at the application level is usually sufficient. However, separating out individual components of blends can still represent a considerable challenge. Irrespective of the Tier 1 methodology chosen, countries will need to report emissions of individual HFCs and PFCs. Information on the practical use of the various commercial types of HFC/PFC refrigerants, blowing agents, solvents, etc. will therefore be required. Many of these products are mixtures of two or more HFCs and/or PFCs, and the composition of fluids for similar purposes may vary according to individual formulas developed by different chemical companies.

Tier 1a – Emission-factor approach at the application level

Tier 1a relies on the availability of basic activity data at the application level, rather than at the level of equipment or product type (sub-application). This activity data may consist of annual chemical consumption data and, for applications exhibiting delayed emissions, banks derived therefrom. Once activity data have been established at the application level, composite emission factors (see Section 7.1.2.3) are then also applied at the application level. These more aggregated emission factors (e.g., all rigid foams) can be a composite or weighted average of the emission factors developed for Tier 2a covering individual equipment or product types, or can be a validated approximation approach (e.g., Gamlen *et al.* 1986).

The calculation formula for Net Consumption within the Tier 1a method is as follows:

$$\text{EQUATION 7.1}$$

$$\text{CALCULATION OF NET CONSUMPTION OF A CHEMICAL IN A SPECIFIC APPLICATION}$$

$$\text{Net Consumption} = \text{Production} + \text{Imports} - \text{Exports} - \text{Destruction}$$

Net Consumption values for each HFC or PFC are then used to calculate annual emissions for applications exhibiting prompt emissions as follows:

$$\text{EQUATION 7.2A}$$

$$\text{CALCULATION OF EMISSIONS OF A CHEMICAL FROM A SPECIFIC APPLICATION}$$

$$\text{Annual Emissions} = \text{Net Consumption} \bullet \text{Composite EF}$$

Where:

Net Consumption = net consumption for the application
 Composite EF = composite emission factor for the application

Note that, as discussed in the Choice of Activity Data section, inventory compilers may have access to chemical consumption data at the aggregate level rather than by application. In this case, it will be necessary as an early step to determine the share of total consumption represented by each application.

In equation 7.1, *Production* refers to production of new chemical. Reprocessing of recovered fluid should not be included in consumption estimates. *Imports* and *Exports* include bulk chemicals but, for a Tier 1 method is unlikely to contain the quantity of chemical contained in products, such as refrigerators, air-conditioners, packaging materials, insulating foams, fire extinguishers etc. unless regional allocation system or other method of approximation has been used. The term *composite emission factor* refers to an emissions rate that summarises the emissions rates of different types of equipment, product or, more generally, sub-applications within an ODS application area. Composite emission factors should account for assembly, operation and, where relevant in the time-series, disposal emissions.

Although destruction of virgin HFCs and PFCs is not currently practised widely, and may be technically difficult in some cases (UNEP TEAP Task Force on Destruction Technologies (UNEP-TEAP, 2002)), it should be included as a potential option to reduce consumption. It should be noted that destruction of virgin chemicals, as considered here, is distinct from the destruction of HFCs and PFCs in the end-of-life phase, which is strictly an emission reduction measure. By-product emissions during HFC/PFC production and fugitive emissions related to production and distribution have to be calculated separately.

Even in simple Tier 1a methods, it is usually necessary to account for the potential development of banks, where these can occur. Banks are the amounts of chemical that have accumulated throughout the lifecycle, either in supply chains, products, equipment or even waste streams but which, as of the end of the most recent year, has not been emitted. At the application level, banks can be estimated using relatively straight-forward algorithms and assumptions provided that the historic Net Consumption is known for each year following the introduction of the substance or, where this period exceeds the average lifetime of the product or equipment, over that average lifetime. Relevant application level emission factors are then applied to the banks to deal with emissions during the lifetime of the products or equipment. This same process is carried out for Tier 2a methods but, in that case, at the sub-application level. More general information on banks is contained in Section 7.1.2.1.

In cases where banks occur, Equation 7.2a is then modified to the following:

$$\text{EQUATION 7.2B}$$

$$\text{CALCULATION OF EMISSIONS OF A CHEMICAL FROM AN APPLICATION WITH BANKS}$$

$$\text{Annual Emissions} = \text{Net Consumption} \bullet \text{Composite EF}_{FY} \\ + \text{Total Banked Chemical} \bullet \text{Composite EF}_B$$

Where:

Net Consumption = net consumption for the application
 Composite EF_{FY} = composite emission factor for the application for first year
 Total Banked Chemical = bank of the chemical for the application
 Composite EF_B = composite emission factor for the application for bank

Composite emission factors are determined by taking an average of the applicable sub-application emission factors, weighted according to the activity in each sub-application. Sub-application emission factors can be country-specific where known or default. In practice, if sub-application data are known, inventory compilers would opt for a Tier 2 (disaggregated approach). If only application level data are known, representative composite emission factors from other studies or default composite emission factors provided in this chapter can be used.

Tier 1b – Mass-balance approach at the application level

The mass balance approach also estimates emissions from assembly, operation, and disposal, but does not rely on emission factors. Instead, the method uses measured consumption (i.e., sales) of each chemical in the country or facility being considered. It is generally limited to ODS Substitutes contained in pressurised systems. The general equation is as follows⁵:

<p>EQUATION 7.3</p> <p>GENERAL MASS BALANCE EQUATION FOR TIER 1B</p> <p><i>Emissions = Annual Sales of New Chemical – (Total Charge of New Equipment – Original Total Charge of Retiring Equipment)</i></p>

Industry needs to purchase new chemical from manufacturers in order to replace leakage (i.e., emissions) from the current equipment stock, or the equipment will not function properly. If the equipment stock did not change from year to year, then annual chemical consumption alone would provide a reasonable estimate of actual leakage or emissions. The total equipment stock, and the chemical charge it contains, however, does change from year to year. Some amount of new equipment containing a chemical charge is introduced each year, and some amount of old equipment that was charged originally is retired each year. If the total chemical charge contained in all equipment is increasing as a result of this annual turnover, then total annual chemical consumption will overestimate emissions (i.e., the charge contained in new equipment is greater than the original charge of the retired equipment). Conversely, if the total chemical charge in all equipment is decreasing, then total annual chemical consumption will underestimate emissions.

In order to make good use of data on annual sales of new chemical, it is therefore also necessary to estimate the total charge contained in new equipment, and the original charge contained in retiring equipment. The total charge of new equipment minus the original total charge of retiring equipment represents the net change in the charge of the equipment stock. (Using the mass balance approach, it is *not* necessary to know the total amount of each chemical in equipment stock in order to calculate emissions.) Where the net change is positive, some of the new chemical is being used to satisfy the increase in the total charge, and therefore cannot be said to replace emissions from the previous year.

Industry also requires new chemical to replace destroyed gas and for stockpiles. Additionally, not all equipment will be serviced annually. Terms can be added to the general equation to account for these factors but are not typically adopted within simple Tier 1b methods.

This approach is most directly applicable to the pressure equipment used in refrigeration and air conditioning, and fire protection applications because these are where chemical sales are most typically used to offset operational emissions. However, since the basic method is relatively simple to apply, it is more typical to extend the approach to the sub-application level (i.e., a Tier 2b method). Further elaboration and modification of this approach is provided in the description of each application. In practice, Tier 1b methods are most commonly used as a further cross-check to Tier 1a methods. Where basic Net Consumption data is lacking, regional and international databases and models have been developed that allocate regional chemical sales for different end uses (sub-applications) at a country level. These can therefore be used to source relevant data.

Tier 2 methods – applied at the sub-application level

There are two versions of the Tier 2 method, both of which result in emission calculations for each individual chemical and distinct types of products or equipment at the sub-application level or within a sub-application. The individual chemicals and products/equipment within the sub-application form the matrix referred to earlier in this section and their analysis is comparable with methods currently applied by the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS) for CFCs, HCFCs and HFCs (McCulloch, Midgley and Ashford, 2001 and 2003; Ashford, Clodic, Kuijpers and McCulloch, 2004).

⁵ Boundary conditions: If there is no net change in the total equipment charge, then annual sales are equal to emissions. If the net change in the total equipment charge is equal to annual sales, then emissions are zero.

Both versions of the Tier 2 methodology follow two general steps:

- a) Calculation or estimation of the time series of net consumption of each individual HFC and PFC chemical at a relatively detailed product and equipment level to establish the consumption basis for emission calculations. (e.g., refrigerators, other stationary refrigeration/AC equipment, appliance foams, insulated panels, pipe insulation, etc.)
- b) Estimation of emissions using the activity data and resulting bank calculations derived from step (i), and either emission factors that reflect the unique emission characteristics related to various processes, products and equipment (Tier 2a) or, relevant new and retiring equipment information at the sub-application level to support a mass balance approach. (Tier 2b).

The difference between Tier 2a and Tier 2b is the same as that for Tier 1a and Tier 1b – namely Tier 2a methods use an emission-factor approach while Tier 2b methods follow a mass-balance approach. Both, however, need to be operated at a level of disaggregation appropriate to a Tier 2 method, typically at least at the sub-application level.

If the requisite data are available, a Tier 2 method is preferred for estimating emissions from ODS substitutes, particularly where the sub-applications within an overall application area are relatively heterogeneous. Some countries may already have the relevant information available to apply a Tier 2 methodology. Other countries might not have access to data for Tier 2 at present, but they are encouraged to establish routines to collect either country-specific or globally or regionally-derived activity data by chemical and sub-application within an application area (e.g., different types of refrigeration and air conditioning sub-applications). Tier 1, in contrast, requires data collection at a more aggregated application level (e.g., refrigeration and air conditioning in its totality).

As a first step in using the Tier 2 method, countries may wish to make first order approximation of the information needed for step (i). This will give direction to more focused data collection efforts in certain application areas or sub-categories. Table 7.3 gives the consumption distribution for all application areas in 2015 for the Article 5 (mainly developing countries) and Non-Article 5 Parties (developed countries) to the Montreal Protocol. The distribution is based on estimated consumption of ODS-substitutes in metric tonnes (UNEP-TEAP 2016b).

Table 7.3a and 7.3b gives the consumption of ODS-substitutes for the application category Refrigeration and Air Conditioning in 2015 for Article 5 and Non-Article 5 Parties, by substance and sub-application.

Table 7.3c shows the share of total consumption used for manufacturing (filling of new equipment) and servicing (refilling of operating equipment).

Good practice guidance in this section deals with variations of the Tier 2 method. Tier 1 methods, covered previously, are generally seen as default methods where the application is not a *key category* and data availability is limited. (Exceptionally, for Fire Protection, Tier 1a method with country-specific activity data and emission factor will be used in the case it is identified as *key category*.) Each sub-section of Sections 7.2 to 7.7 discusses how to apply these methods to specific ODS applications, reviews existing data sources, and identifies gaps therein.

Country	Refrigeration and Air conditioning	Aerosols	Foam blowing agents	Fire protection and others
Article 5 Parties ^a	88 %	6 %	3 %	3 %
Non-Article 5 Parties ^a	57 %	22 %	19 %	2 %

Source: UNEP-TEAP (2016b)

^a See list of Article 5 and Non-Article 5 Parties to the Montreal protocol at the Unep Ozone Secreteriat web page

	Total	HFC-134a	R-410A	R-407C	R-404A	R-507
TOTAL	100	27	39	20	7	7
Stationary Air Conditioning	60	1	39	20	-	-
Mobile Air Conditioning	19	19	-	-	-	-
Commercial Refrigeration ^{b)}	13	2	-	-	6	6
Domestic Refrigeration	5	5	-	-	-	-
Industrial Refrigeration ^{b)}	2	<1	-	-	1	1
Transport Refrigeration ^{b)}	1	<1	-	-	<1	<1

Source: UNEP (2017)

^a See list of Article 5 Parties to the Montreal protocol at the Unep Ozone Secreteriat web page

^b Due to rounding, sums of individual items may not equal the totals

	Total	HFC-134a	R-410A	R-407C	R-404A
TOTAL	100	39	39	13	9
Stationary Air Conditioning	54	2	39	13	-
Mobile Air Conditioning	34	34	-	-	-
Commercial Refrigeration	11	2	-	-	8
Industrial Refrigeration			-	-	1
Transport Refrigeration			-	-	-
Domestic Refrigeration	1	1	-	-	-

Source: UNEP-TEAP (2016b)

^a See list of Article 5 Parties to the Montreal protocol at the Unep Ozone Secreteriat web page

	Manufacturing	Servicing
Article 5 Parties ^a	68	32
Non-Article 5 Parties ^a	53	47

Source: UNEP-TEAP (2016b)

^a See list of Article 5 and Non-Article 5 Parties to the Montreal protocol at the Unep Ozone Secreteriat web page

Tier 2a – Emission-factor approach

The country-specific data required for a Tier 2a approach are derived from the number of products and end-uses relevant to each sub-application in which ODS substitutes are contained and from which ODS substitutes are ultimately emitted. This approach seeks information on the number of equipment units or products that use these chemicals, average chemical charges, average service life, emission rates, recycling, disposal, and other pertinent parameters. This information is generally collected at the level of distinct groups of products or equipment (e.g., for rigid foams: integral skin, continuous panel, discontinuous panel, appliance, injected foam products and others). Annual emissions are then estimated as a function of these parameters through the life of the units or products by the application of emission factors that are relevant to the lifecycle phases. Since equipment and other products vary significantly in the amount of chemical used, service life, and emission rates, the characterisation of this equipment can be a resource intensive task. The longer-lived the end-use equipment or

product, and the more diverse the types of equipment or product within a particular sub-application, the more complex the sourced data approach has to be in order to account for emissions. However, the approach can provide an accurate estimate of emissions if the data called for by the following equation are available for all relevant types and vintages of equipment or product:

<p>EQUATION 7.4</p> <p>SUMMARY EMISSIONS EQUATION BASED ON PHASES OF THE LIFECYCLE</p> <p><i>Total Emissions of Each PFC or HFC = Assembly/Manufacturing Emissions</i></p> <p style="padding-left: 40px;"><i>+ Operation Emissions</i></p> <p style="padding-left: 40px;"><i>+ Disposal Emissions</i></p>

Manufacturing or Assembly Emissions occur as fugitives when new equipment is filled for the first time with a chemical or when a product is manufactured. *Operational Emissions* from equipment and products occur as leaks or by diffusion during the use phase of the product or equipment (including servicing). In some cases, there can even be intentional releases during operation. Finally, *Disposal Emissions* can occur when the equipment or product reaches its end-of-life and is decommissioned and disposed of. In this case, the remaining HFC/PFC in the product or equipment may escape to the atmosphere, be recycled, or possibly destroyed.

As with the Tier 1a method, there is a need to make provision for the development of banks in some applications. This can lead to complex multiple calculations at the sub-application level, since the dynamics of banks may vary considerably. However, because the individual algorithms rely on a simple sequential calculation of non-emitted consumption (i.e., consumption – emissions for each successive year), excellent emission assessments can result from a well-constructed and well-maintained national model.

The need to update equipment and product inventories on an annual basis can be a major implementation challenge for inventory compilers with limited resources. This challenge is made somewhat easier because it may not be necessary to collect annual chemical consumption if a comprehensive set of other market parameters is available (e.g., number of domestic refrigerators produced, etc.) In some countries or regions, trade associations can be a significant source of such data. Otherwise, specific market research may be necessary. Where such market parameters are the primary source of activity data, the potential magnitude of errors that can be introduced by small discrepancies at unit level makes it *good practice* to carry out a chemical consumption data cross-check to act as a means of providing quality assurance. The relevant QA/QC sections of this chapter give guidance on how to conduct such cross-checks for each relevant application.

In order to limit the burden of data management for both annual consumption data and the status of banks, it is possible to access international and regional databases of such information to gain the necessary inputs of globally or regionally validated data to maintain a national model. These databases can also help to overcome any confidentiality barriers that may exist in collecting and/or publishing data at a national level, particularly where the number of suppliers is low. More information on the use of such databases is contained in Section 7.1.2.4 and Box 7.1.

Even where comprehensive country-specific activity data exists at a country level, it is *good practice* to benchmark outputs against assessments made from databases of globally or regionally derived data. This need not be done on an annual basis but could reasonably be conducted every 2-3 years. Significant discrepancies can then be analysed and suitable actions taken to reconcile differences.

Tier 2b – Mass-balance approach

Tier 2 mass-balance approaches are similar to those described for Tier 1b, except that the process is applied at the sub-application level. This is a particularly valuable approach for the refrigeration sector where there are a significant number of relatively heterogeneous sub-applications. As is also the case for Tier 1 methods, it is not uncommon to see mass-balance approaches used in combination with emission-factor approaches to ensure that the outputs achieved are as robust as possible. Such approaches can realistically be described as hybrid Tier 2a/b methods and they will be identified as such, where they occur in the relevant application-specific sections that follow.

Since mass-balance approaches also require activity data at the sub-application level, it may be more resource-efficient to use global or regional databases to obtain appropriate globally or regionally validated data. The same criteria for selection as set out for Tier 2a methods also apply for Tier 2b methods. Accordingly, equal care should be taken in selecting validated datasets.

7.1.2.3 CHOICE OF EMISSION FACTORS

No refinement.

7.1.2.4 CHOICE OF ACTIVITY DATA

No refinement.

7.1.2.5 COMPLETENESS

No refinement.

7.1.2.6 DEVELOPING A CONSISTENT TIME SERIES

No refinement.

7.1.3 Uncertainty assessment

No refinement.

7.1.4 Quality Assurance/Quality Control (QA/QC), Reporting and Documentation for all ODS substitutes applications

No refinement.

7.2 SOLVENTS (NON-AEROSOL)

No refinement.

7.3 AEROSOLS (PROPELLANTS AND SOLVENTS)

No Refinement.

7.4 FOAM BLOWING AGENTS

No refinement.

7.5 REFRIGERATION AND AIR CONDITIONING

7.5.1 Chemicals covered in this application area

Refrigeration and air-conditioning (RAC) systems may be classified in up to six sub-application domains or categories (UNEP-RTOC, 2003), although fewer sub-applications may be used in some countries. These categories correspond to sub-applications that may differ by location and purpose, and are listed below:

- a) Domestic (i.e., household) refrigeration,
- b) Commercial refrigeration including different types of equipment, from vending machines to centralised refrigeration systems in supermarkets,
- c) Industrial processes including chillers, cold storage, and industrial heat pumps used in the food, petrochemical and other industries,
- d) Transport refrigeration including equipment and systems used in refrigerated trucks, containers, reefers, and wagons,
- e) Stationary air conditioning including air-to-air systems, heat pumps, and chillers⁶ for building and residential applications,
- f) Mobile air-conditioning systems used in passenger cars, truck cabins, buses, and trains.⁷

For all these sub-applications, different HFCs are progressively replacing CFCs and HCFCs. For example, in developed and several developing countries, HFC-134a has replaced CFC-12 in domestic refrigeration, high-pressure chillers and mobile air conditioning systems, and blends of HFCs such as R-407C (HFC-32/HFC-125/HFC-134a) and R-410A (HFC-32/HFC-125) are replacing HCFC-22 mainly in stationary air conditioning. HFC blends R-404A (HFC-125/HFC-143a/HFC-134a) and R-507A (HFC-125/HFC-143a) have replaced R-502 (CFC-22/CFC-115) and HCFC-22 in commercial refrigeration. Other, non-HFC substances are also used to replace CFCs and HCFCs such as iso-butane (HC-600a) in domestic refrigeration or ammonia in industrial refrigeration.

A large number of blends containing HFCs and/or PFCs are being used in Refrigeration and Air Conditioning applications. Table 7.8 shows some of these blends. A more comprehensive list can be obtained at the UNEP Ozone Secretariat web site (<https://ozone.unep.org/sites/default/files/Data-Reporting-Instructions-English.2019-03-20.pdf>) or by contacting The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).

⁶ Comfort air conditioning in large commercial buildings (including hotels, offices, hospitals, universities, etc.) is commonly provided by water chillers coupled with an air handling and distribution system.

⁷ The sub-application of mobile air conditioning systems is likely to represent the largest share of HFC emissions within the Refrigeration and Air Conditioning application for many countries. See Section 7.5.2.4, Applying Tier 2 Methods – The Example Of Mobile Air Conditioning (MAC), for an example of how to calculate these emissions. The reader will see that limited information is needed to approximate these emissions, and essentially becomes a simple multiplication of an average emission factor and the number of cars with HFC air conditioning, and possibly adding emissions relating to container management, charging and end-of-life.

TABLE 7.8
BLENDS (MANY CONTAINING HFCs AND/OR PFCs)

Blend	Constituents	Composition (%)
R-400	CFC-12/CFC-114	Should be specified ¹
R-401A	HCFC-22/HFC-152a/HCFC-124	(53.0/13.0/34.0)
R-401B	HCFC-22/HFC-152a/HCFC-124	(61.0/11.0/28.0)
R-401C	HCFC-22/HFC-152a/HCFC-124	(33.0/15.0/52.0)
R-402A	HFC-125/HC-290/HCFC-22	(60.0/2.0/38.0)
R-402B	HFC-125/HC-290/HCFC-22	(38.0/2.0/60.0)
R-403A	HC-290/HCFC-22/PFC-218	(5.0/75.0/20.0)
R-403B	HC-290/HCFC-22/PFC-218	(5.0/56.0/39.0)
R-404A	HFC-125/HFC-143a/HFC-134a	(44.0/52.0/4.0)
R-405A	HCFC-22/ HFC-152a/ HCFC-142b/PFC-318	(45.0/7.0/5.5/42.5)
R-406A	HCFC-22/HC-600a/HCFC-142b	(55.0/14.0/41.0)
R-407A	HFC-32/HFC-125/HFC-134a	(20.0/40.0/40.0)
R-407B	HFC-32/HFC-125/HFC-134a	(10.0/70.0/20.0)
R-407C	HFC-32/HFC-125/HFC-134a	(23.0/25.0/52.0)
R-407D	HFC-32/HFC-125/HFC-134a	(15.0/15.0/70.0)
R-407E	HFC-32/HFC-125/HFC-134a	(25.0/15.0/60.0)
R-408A	HFC-125/HFC-143a/HCFC-22	(7.0/46.0/47.0)
R-409A	HCFC-22/HCFC-124/HCFC-142b	(60.0/25.0/15.0)
R-409B	HCFC-22/HCFC-124/HCFC-142b	(65.0/25.0/10.0)
R-410A	HFC-32/HFC-125	(50.0/50.0)
R-410B	HFC-32/HFC-125	(45.0/55.0)
R-411A	HC-1270/HCFC-22/HFC-152a	(1.5/87.5/11.0)
R-411B	HC-1270/HCFC-22/HFC-152a	(3.0/94.0/3.0)
R-411C	HC-1270/HCFC-22/HFC-152a	(3.0/95.5/1.5)
R-412A	HCFC-22/PFC-218/HCFC-142b	(70.0/5.0/25.0)
R-413A	PFC-218/HFC-134a/HC-600a	(9.0/88.0/3.0)
R-414A	HCFC-22/HCFC-124/HC-600a/HCFC-142b	(51.0/28.5/4.0/16.5)
R-414B	HCFC-22/HCFC-124/HC-600a/HCFC-142b	(50.0/39.0/1.5/9.5)
R-415A	HCFC-22/HFC-152a	(82.0/18.0)
R-415B	HCFC-22/HFC-152a	(25.0/75.0)
R-416A	HFC-134a/HCFC-124/HC-600	(59.0/39.5/1.5)
R-417A	HFC-125/HFC-134a/HC-600	(46.6/50.0/3.4)
R-418A	HC-290/HCFC-22/HFC-152a	(1.5/96.0/2.5)
R-419A	HFC-125/HFC-134a/HE-E170	(77.0/19.0/4.0)
R-420A	HFC-134a/HCFC-142b	(88.0/12.0)
R-421A	HFC-125/HFC-134a	(58.0/42.0)

TABLE 7.8 (CONTINUED)
BLENDS (MANY CONTAINING HFCs AND/OR PFCs)

Blend	Constituents	Composition (%)
R-422A	HFC-125/HFC-134a/HC-600a	(85.1/11.5/3.4)
R-422B	HFC-125/HFC-134a/HC-600a	(55.0/42.0/3.0)
R-422C	HFC-125/HFC-134a/HC-600a	(82.0/15.0/3.0)
R-500	CFC-12/HFC-152a	(73.8/26.2)
R-501	HCFC-22/CFC-12	(75.0/25.0)
R-502	HCFC-22/CFC-115	(48.8/51.2)
R-503	HFC-23/CFC-13	(40.1/59.9)
R-504	HFC-32/CFC-115	(48.2/51.8)
R-505	CFC-12/HCFC-31	(78.0/22.0)
R-506	CFC-31/CFC-114	(55.1/44.9)
R-507A	HFC-125/HFC-143a	(50.0/50.0)
R-508A	HFC-23/PFC-116	(39.0/61.0)
R-508B	HFC-23/PFC-116	(46.0/54.0)
R-509A	HCFC-22/PFC-218	(44.0/56.0)

¹ R-400 can have various proportions of CFC-12 and CFC-114. The exact composition needs to be specified, e.g., R-400 (60/40).

7.5.2 Methodological issues

7.5.2.1 CHOICE OF METHOD

As discussed in the introductory section to this chapter, both Tier 1 and Tier 2 result in estimates of *actual* emissions rather than estimates of *potential* emissions. Actual estimates, which account for the lag between consumption and emissions, are particularly important for both the refrigeration and air conditioning sector because of the potentially long retention of refrigerants in products and equipment utilised in these applications.

The options available to the refrigeration and air conditioning application are shown in the decision tree shown in Figure 7.6.

TIER 1

Tier 1 a/b

It is expected that the refrigeration and air conditioning will be a *key category* for many countries. The implication of this conclusion from Table 7.2 and the decision tree in Figure 7.6 is that either country-specific or globally or regionally derived activity data will be required at the sub-application (disaggregated) level in order to complete the reporting task. However, in the rare instances that the refrigeration and air conditioning application is much less significant, there should be available a suitable Tier 1 method for aggregated data.

From experience of studying the dynamics of refrigerant consumption and banks in several countries (UNEP-RTOC, 2003; Ashford, Clodic, Kuijpers and McCulloch, 2004; and supporting materials), it is possible to derive assumptions that allow for the assessment of the use of refrigerant that may help in assessing sales of a given refrigerant at a country level. Such a hybrid Tier 1a/b approach may use the following assumptions:

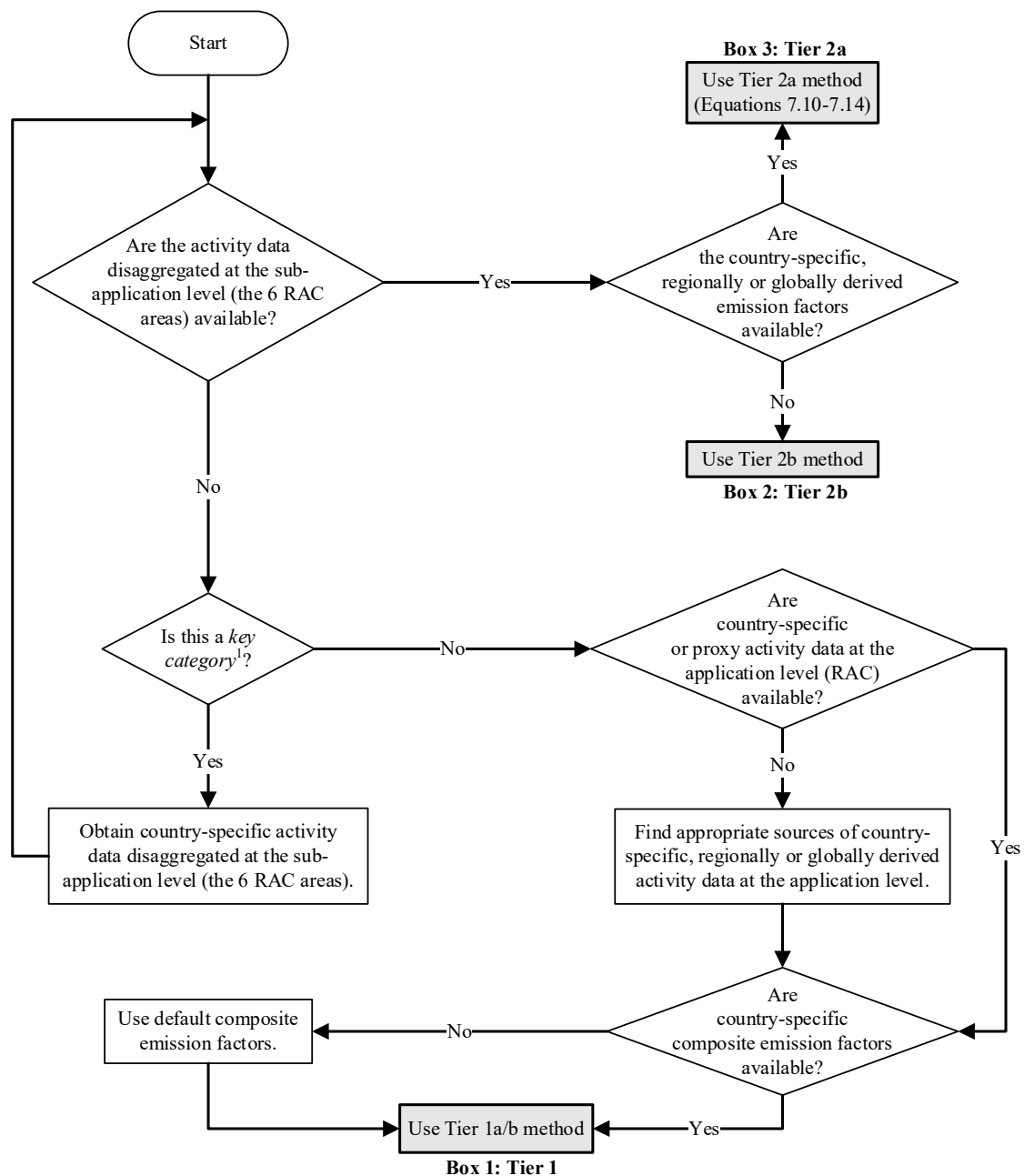
1. Servicing of equipment containing the refrigerant does not commence until 3 years after the equipment is installed.
2. Emissions from banked refrigerants average 15 percent annually across the whole RAC application area. This assumption is estimated to be a weighed average across all sub-applications, for which default emission factors are shown in Table 7.9.
3. In a mature market two thirds of the sales of a refrigerant are used for servicing and one third is used to charge new equipment. A mature market is one in which ODS substitute-employing refrigeration equipment is in wide use, and there are relationships between suppliers and users to purchase and service equipment.
4. The average equipment lifetime is 15 years. This assumption is also estimated to be a weighed average across all sub-applications.
5. The complete transition to a new refrigerant technology will take place over a 10 year period. From experiences to date, this assumption is believed to be valid for a single chemical in a single country.

With these assumptions in place, it is possible to derive emissions, if the following data can be provided:

- Sales of a specific refrigerant in the year to be reported
- Year of introduction of the refrigerant
- Growth rate in sales of new equipment (usually assumed linear across the period of assessment)
- Assumed percentage of new equipment exported
- Assumed percentage of new equipment imported

The Tier 1a/b method then back-calculates the development of banks of a refrigerant from the current reporting year to the year of its introduction. In mapping this period, the method also models the transition from sales to new equipment (100 percent initially) to the mature market position assumed based on experience to be 33 percent to new equipment and 67 percent to servicing requirements. It is assumed that the transition to new refrigerant technology is reflected identically in any imported equipment.

Figure 7.6 Decision tree for actual emissions from the refrigeration and air conditioning (RAC) application



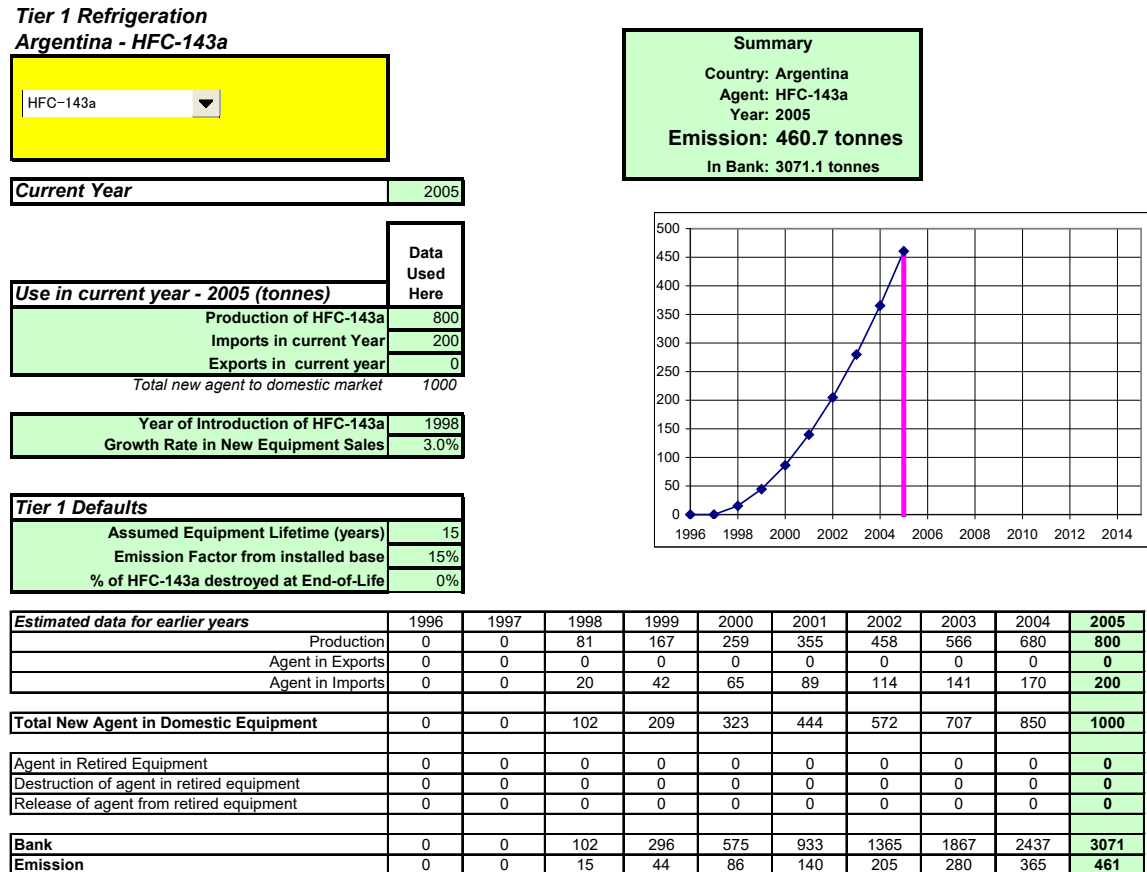
Note:

1. See Volume 1 Chapter 4, Methodological Choice and Identification of Key Categories (noting Section 4.1.2 on limited resources), for discussion of *key categories* and use of decision trees.

The following spreadsheet example indicates how the Tier 1a/b method would estimate a seven-year time series of emissions of the selected refrigerant, following its initial introduction in 1998, with the knowledge that there were sales of 1 000 tonnes in 2005. The spreadsheet contained in the 2006 IPCC Guidelines CDROM mirrors this calculation, and globally or regionally derived datasets⁸ at both application and consolidated sub-application levels should be available at a country level to assist in completion of this spreadsheet.

⁸ As noted in Box 7.1, inclusion in the IPCC Emission Factor Database (EFDB) will indicate general adherence to due process, but it is *good practice* for countries to ensure that all data taken from the EFDB are appropriate for their national circumstances.

Figure 7.7 Example of spreadsheet calculation for Tier 1a/b assessments



In this hypothetical example, the production of a specific refrigerant are 800 tonnes with an additional 200 tonnes in imported equipment, in 2005 making a total consumption of 1 000 tonnes. Based on this consumption figure and knowledge of the year of introduction of the refrigerant, it can be seen that the Tier 1a/b method predicts emissions of 461 tonnes based on the development of banks over the previous seven years. The bank in 2005 is estimated at 3 071 tonnes.

It should be noted that, while such methods allow for the estimation of emissions when data are difficult to obtain, it is still necessary to have an accurate assessment of country-specific or globally or regionally derived net consumption activity data. When the content of Table 7.8 is considered (particularly when some of these blends may be being imported in equipment) it is clear that there needs to be considerable knowledge of technology selection in the market. Refrigerant suppliers should be able to assist inventory compilers in this area, but the burden of developing high quality activity datasets may lead inventory compilers to the conclusion that Tier 2 options provide more value with little extra work. Indeed, where globally or regionally validated data activity is sought, this will normally be a reconstitution of disaggregated data originally at the sub-application level, so it might be most logical to take full advantage of that versatility and pursue a Tier 2 approach from the outset.

TIER 2

Overview

The Tier 2a methodology:

- Takes into account the phase out or the phase down of CFCs and HCFCs depending on the Montreal Protocol schedule and possible national or regional regulations, in order to establish the refrigerant choice for all applications;
- Defines the typical refrigerant charge and the equipment lifetime per sub-application;
- Defines the emission factors for refrigerant charge, during operation, at servicing and at end-of-life.

Calculation of emissions throughout the equipment lifetime requires deriving the total stock of equipment independent of their vintage. In doing so the refrigerant bank is established per sub-application.

In order to achieve consistency it is suggested to derive the annual market of refrigerants from the refrigerant quantities charged in the brand new equipment and from the refrigerant quantities used for servicing of the total stock of equipment.

The Tier 2b mass-balance approach relies on a knowledge of the annual sales of refrigerant, refrigerant destroyed and any changes in equipment stock that occur (i.e., new equipment sales and equipment decommissioned) on a sub-application basis. It does not require an absolute knowledge of equipment stocks or emission factors relating to each refrigeration and air conditioning sub-application.

Examples of how the Tier 2 methodology may be applied are given in the remainder of this section.

Tier 2b - Mass-balance approach

The mass-balance approach is particularly applicable to the Refrigeration and Air Conditioning application because of the significant servicing component required to maintain equipment. The general approach to Tier 2b is introduced in Chapter 1 of Volume 3.

For the mass-balance approach, the four emission stages (charging, operation servicing and end-of-life) identified above are addressed in the following simplified equation:

<p>EQUATION 7.9</p> <p>DETERMINATION OF REFRIGERANT EMISSIONS BY MASS BALANCE</p> $ \begin{aligned} \text{Emissions} = & \text{Annual Sales of New Refrigerant} - \text{Total Charge of New Equipment} \\ & + \text{Original Total Charge of Retiring Equipment} - \text{Amount of Intentional Destruction} \end{aligned} $
--

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

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

Original Total Charge of Retiring Equipment is the sum of the full charges of all the retiring equipment decommissioned in a country in a given year. It assumes that the equipment will have been serviced right up to its decommissioning and will therefore contain its original charge.

Amount of Intentional Destruction is that quantity of the chemical duly destroyed by a recognised destruction technology.

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

- To increase the size of the existing chemical stock (bank) in use (including retrofitting equipment from a previous chemical to the given chemical);
- To replace that fraction of last year's stock of chemical that was emitted to the atmosphere (through, for example, leaks or servicing losses);
- To provide supply-chain priming or stockpiles.

Since the third item in this list is rarely required in a steady-state market, it is not included in Equation 7.9. Terms to account for stockpiling and retrofitting could be added to Equation 7.9 if such situations exist.

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

By using data on current and historical sales of gas, rather than emission factors referenced from literature, the equation reflects assembly, operation, and disposal emissions at the time and place where they occur. Default emission factors may not be accurate because emissions rates may vary considerably from country to country and even within a single country.

As discussed in Chapter 1, Section 1.5 of Volume 3, one drawback of the mass-balance approach is that it can underestimate emissions when equipment stocks are growing, because there is a lag between the time the emissions occur and the time they are detected (through equipment servicing). This underestimate will be

relatively large in countries where HFCs have been used in equipment for less than ten years, because much of the equipment will have leaked without ever being serviced. Thus, countries where HFCs have been used for less than ten years are encouraged to estimate emissions using alternative approaches. In general, the longer HFCs are used in a country, the smaller the underestimate associated with the mass-balance approach. Once equipment containing HFCs begins to retire, the underestimate declines to a low level.

Equation 7.9 can be applied either to individual types of equipment (sub-applications), or more generally to all air conditioning and refrigeration equipment in a country (i.e., Tier 1b), depending on the level of disaggregation of available data. If disaggregated data are available, emissions estimates developed for each type of equipment and chemical are summed to determine total emissions for the application.

Tier 2a – Emission-factor approach

In a Tier 2a calculation, refrigerant emissions at a year t from each of the six⁹ sub-applications of refrigeration and air conditioning systems are calculated separately. These emissions result from:

- $E_{\text{containers},t}$ = emissions related to the management of refrigerant containers
- $E_{\text{charge},t}$ = emissions related to the refrigerant charge: connection and disconnection of the refrigerant container and the new equipment to be charged
- $E_{\text{lifetime},t}$ = annual emissions from the banks of refrigerants associated with the six sub-applications during operation (fugitive emissions and ruptures) and servicing
- $E_{\text{end-of-life},t}$ = emissions at system disposal

All these quantities are expressed in kilograms and have to be calculated for each type of HFC used in the six different sub-applications.

EQUATION 7.10
SUMMARY OF SOURCES OF EMISSIONS

$$E_{\text{total},t} = E_{\text{containers},t} + E_{\text{Charge},t} + E_{\text{lifetime},t} + E_{\text{end-of-life},t}$$

Methods for estimating average emission rates for the above-mentioned sectors are outlined below and need to be calculated on a refrigerant by refrigerant basis for all equipment regardless of their vintage. If information on container and charging emissions is not available, inventory compilers can estimate these losses as a percent of the bank and revise the lifetime (operation plus servicing) emission factor in Equation 7.13 below to account for such losses.

Refrigerant management of containers

The emissions related to the refrigerant container management comprises all the emissions related to the refrigerant transfers from bulk containers (typically 40 tonnes) down to small capacities where the mass varies from 0.5 kg (disposable cans) to 1 tonne (containers) and also from the remaining quantities - the so-called refrigerant *heels* (vapour and /or liquid) - left in the various containers, which are recovered or emitted.

EQUATION 7.11
SOURCES OF EMISSIONS FROM MANAGEMENT OF CONTAINERS

$$E_{\text{containers},t} = RM_t \cdot \frac{c}{100}$$

Where:

- $E_{\text{containers},t}$ = emissions from all HFC containers in year t , kg
- RM_t = HFC market for new equipment and servicing of all refrigeration application in year t , kg
- c = emission factor of HFC container management of the current refrigerant market, percent

The emissions related to the complete refrigerant management of containers are estimated between 2 and 10 percent of the refrigerant market.

Refrigerant charge emissions of new equipment

⁹ More than six sub-applications can be used, depending on the level of disaggregated data available.

The emissions of refrigerant due to the charging process of new equipment are related to the process of connecting and disconnecting the refrigerant container to and from the equipment when it is initially charged.

EQUATION 7.12
SOURCES OF EMISSIONS WHEN CHARGING NEW EQUIPMENT

$$E_{charge,t} = M_t \cdot \frac{k}{100}$$

Where:

- $E_{charge,t}$ = emissions during system manufacture/assembly in year t, kg
 M_t = amount of HFC charged into new equipment in year t (per sub-application), kg
 k = emission factor of assembly losses of the HFC charged into new equipment (per sub-application), percent

Note: the emissions related to the process of connecting and disconnecting during servicing are covered in Equation 7.13.

The amount charged (M_t) should include all systems which are charged in the country, including those which are produced for export. Systems that are imported pre-charged should not be considered.

Typical range for the emission factor k varies from 0.1 to 3 percent. The emissions during the charging process are very different for factory assembled systems where the emissions are low (see Table 7.9) than for field-erected systems where emissions can be up to 2 percent.

Emissions during lifetime (operation and servicing)

Annual leakage from the refrigerant banks represent fugitive emissions, i.e., leaks from fittings, joints, shaft seals, etc. but also ruptures of pipes or heat exchangers leading to partial or full release of refrigerant to the atmosphere. Besides component failures, such as compressor burn-out, equipment is serviced mainly when the refrigerating capacity is too low due to loss of refrigerant from fugitive emissions. Depending on the application, servicing will be done for instance every year or every three years, or sometimes not at all during the entire lifetime such as in domestic refrigeration sub-applications. For some sub-applications, leaks have to be fixed during servicing and refrigerant recovery may be necessary, so the recovery efficiency has to be taken into account when estimating emission factors. In addition, knowing the annual refrigerant needs for servicing per sub-application allows the determination of the national refrigerant market by adding the refrigerant quantities charged in new equipment (see Paragraph Quality assurance/Quality control). The following calculation formula applies:

EQUATION 7.13
SOURCES OF EMISSIONS DURING EQUIPMENT LIFETIME

$$E_{lifetime,t} = B_t \cdot \frac{x}{100}$$

Where:

- $E_{lifetime,t}$ = amount of HFC emitted during system operation in year t, kg
 B_t = amount of HFC banked in existing systems in year t (per sub-application), kg
 x = annual emission rate (i.e., emission factor) of HFC of each sub-application bank during operation, accounting for average annual leakage and average annual emissions during servicing, percent

In calculating the refrigerant bank (B_t) all systems in operation in the country (produced domestically and imported) have to be considered on a sub-application by sub-application basis.

Examples of typical leakage rates (x) for various types of equipment describing the respective refrigeration sub-applications are given in Table 7.9.

Emissions at end-of-life

The amount of refrigerant released from scrapped systems depends on the amount of refrigerant left at the time of disposal, and the portion recovered. From a technical point of view, the major part of the remaining fluid can be recovered, but recovery at end-of-life depends on regulations, financial incentives, and environmental consciousness.

The following calculation formula (Equation 7.14) is applicable to estimate emissions at system disposal:

EQUATION 7.14
EMISSIONS AT SYSTEM END-OF-LIFE

$$E_{\text{end-of-life}, t} = M_{t-d} \cdot \frac{p}{100} \cdot \left(1 - \frac{\eta_{\text{rec}, d}}{100}\right)$$

Where:

$E_{\text{end-of-life}, t}$ = amount of HFC emitted at system disposal in year t, kg

M_{t-d} = amount of HFC initially charged into new systems installed in year (t-d), kg

p = residual charge of HFC in equipment being disposed of expressed in percentage of full charge, percent

$\eta_{\text{rec}, d}$ = recovery efficiency at disposal, which is the ratio of recovered HFC referred to the HFC contained in the system, percent

In estimating the amount of refrigerant initially charged into the systems (M_{t-d}), all systems charged in the country (for the domestic market) and systems imported pre-charged should be taken into account.

BOX 7.2A (NEW)**HOW TO BUILD A REFRIGERATION AND AIR-CONDITIONING (R/AC) EMISSION INVENTORY IN A FEW SIMPLE STEPS. TIER 1 AND TIER 2 EMISSION FACTOR APPROACHES****Learn about the use of HFCs in R/AC**

Tip! The “Fact sheets on HFCs” provided at the UNEP Ozone Secretariat web site, particularly the overview of HFC market sectors, is a good starting point for learning about the use of these chemicals. (See http://conf.montreal-protocol.org/meeting/workshops/hfc_management-02/presession/English/Forms/AllItems.aspx)

TIER 1a/b**1. The IPCC Worksheet**

A basic calculation tool in the form of MS Excel worksheet “Calculation Example for 2F1” can be downloaded at the IPCC web site (<https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol3.html>).

2. Activity Data

Collect the data required as inputs to the calculations:

- Consumption of specific HFCs or other ODS substitutes, at least in the year to be reported
- Year of introduction of the refrigerant
- Growth rate in sales of new equipment

Look for data in, for example, Refrigerant Management Plans (RMPs), HCFC Phase-out Management Plans (HPMPs) or data reported under the Montreal Protocol. To get an idea of the most important gas types and application areas, see Tables 7.3a-d.

3. Emission Factors

Identify and apply the appropriate emission factors. The IPCC Worksheet contains the default Tier 1 emission factor. Modify the default emission factor according to country-specific conditions if information on these conditions is available.

TIER 2a

Where refrigeration and air conditioning is a *key category*, a Tier 2 approach should be used to estimate emissions. Building a good quality Tier 2 inventory for refrigerants is demanding, so setting up a plan for gradual improvement over time is recommended.

1. Calculation tools

The spreadsheet "Calculation example for 2F1 (Tier 2)" of the *2019 Refinement* can be used. Most countries have however built their own models, which are adapted to national conditions and to the data they have available.

2. Activity data

For the Tier 2 approach HFC consumption needs to be collected or estimated for each of the six sub-applications listed in Section 7.5.1.

Box 7.2b and Box 7.2c gives information on what data needs to be collected.

Data sources are described in Box 7.3a.

3. Emission factors

Table 7.9 provides ranges of default factors for the sub-applications if country-specific factors are not available. Choose from the ranges according to country-specific conditions and document the reasons for the choices. In general, the emission factors in the low end of the ranges apply for developed countries or those that have a voluntary or mandatory system in place to limit emissions during equipment service, use and disposal. Further discussion on the choice of emission factors is found in section 7.5.2.2.

BOX 7.2B (NEW)**THE BASIC ELEMENTS OF AN EMISSION INVENTORY FOR R/AC**

Emissions of HFCs from refrigeration and air conditioning (R/AC) equipment are closely related to the amounts and types of chemicals in the bank of a country. A "bank" is the amount of HFCs and other fluorinated ODS-substitutes contained in equipment in use. It is therefore important for the inventory compiler to keep track of the bank and the flows of chemicals into and out of the bank. The following equation summarizes how the bank changes over the year due to emissions and other flows. More details are given in the spreadsheet "Calculation example for 2F1 (Tier 2)".

Estimation of annual refrigerant bank

$$Bank_y = Bank_{y-1} + Addition_y - Removal_y$$

Where:

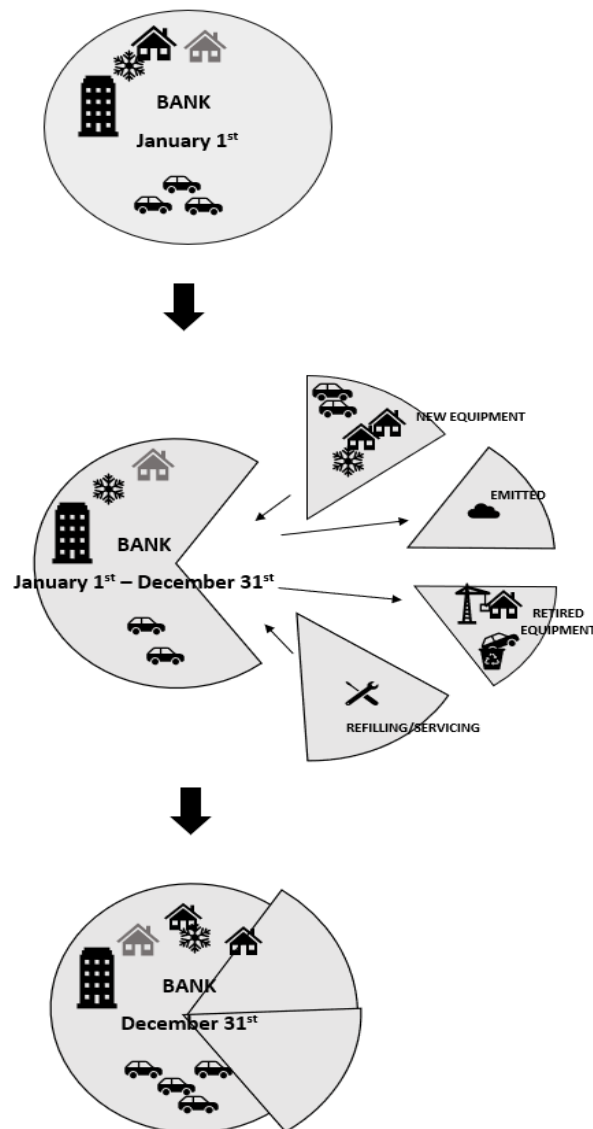
$Bank_y$ = Refrigerant bank on December 31st of year y, kg

$Bank_{y-1}$ = Refrigerant bank on December 31st of year y-1/January 1st of year y, kg

$Addition_y$ = Addition of new substances year y, kg

$Removal_y$ = Removal of substances exported, emitted or destroyed year y, kg

The figure below illustrates these relationships.



BOX 7.2B (NEW) (CONTINUED)
THE BASIC ELEMENTS OF AN EMISSION INVENTORY FOR R/AC

The Bank of HFCs

The starting point for the annual estimates is a *snapshot of the bank* of HFCs at the end of the previous year/beginning of the current year.

The bank is the amount of HFCs contained in equipment in use in a country, and a snapshot of the bank means that for each of the relevant sub-applications, you need to have an estimate of the types and amounts of HFCs it contains. For instance, you need to quantify the amount of HFC-134a in air conditioning units in cars, the amount of the blend R-410A in air conditioning used in buildings, R-404A used for refrigeration in supermarkets etc. See the list of chemicals and the equipment (sub-applications) in which they are normally contained in Table 7.1. Note that in a given year, equipment may contain substances other than HFCs. If this is the case, you need to estimate the share of HFCs in relation to the other substances (e.g. HCFC, NH₃, etc.).

If you start the calculations at the beginning of the first year of HFCs entering the market in your country, there is no bank of chemicals and the bank at January 1st of year $y = 0$.

If you start making the inventory when HFCs are already in use in your country, you will have to spend time putting together information on what the bank currently looks like. See Box 7.2c on how to estimate the bank if the starting point of the inventory is not the first year of using HFC, i.e. when the bank at January 1st of year $y > 0$.

In the future, this kind of snapshot of the equipment population (bank) will be one of the outputs from the calculation model you run every year.

The flows of HFCs into and out of the bank

The bank will develop year by year depending on the amounts of HFC added to and removed from the bank. In order to keep track of the development of the bank, you need to collect data on or estimate these flows:

Flow of HFCs into the bank

HFC is mainly added to the bank through two processes: New equipment containing HFCs and the servicing (refilling) of equipment in use.

A common approach for quantifying the sum of the amount of HFC contained in new equipment added to the bank and the amount used for servicing, is to collect data on domestic sales of HFCs both **in bulk** and **in equipment**. Domestic sale is then the sum of **production** and **imports**, minus **exports**. If HFC is recovered in a country, this also needs to be taken into account, as the amount of HFCs recycled remains in the bank.

Only a few countries produce HFCs. This means that when collecting data for domestic sales of HFCs in bulk, most inventory compilers will solely need to quantify the imports. Ideally, you want to know the amount of each kind of HFC imported to your country, and what kind of sub-application it will be used in. You also need to collect data on (or estimate), the amount of HFC used for filling (production) of new equipment as opposed to the servicing of equipment already in use.

New equipment

HFC in new equipment is added to the bank when equipment is filled in the country or imported prefilled. HFC in exported equipment should not be added to the bank. See the spreadsheet "Calculation example for 2F1 (Tier 2)" for a detailed description on how to estimate the amount of HFCs entering the bank through new equipment and the emissions from this flow of chemicals.

BOX 7.2B (NEW) (CONTINUED)
THE BASIC ELEMENTS OF AN EMISSION INVENTORY FOR R/AC

For example, if your country does not produce HFC-134a or manufacture cars (i.e. fill air conditioning units of new cars with this chemical), the annual addition of HFC-134a through new cars will only consist of the amount contained in imported cars. If your country does manufacture cars, but does not produce HFCs, the annual addition in new equipment will consist of HFC-134a contained in imported cars *and* the amount of HFC-134a imported in bulk for filling (manufacturing) of new cars, minus the amount contained in exported cars.

See box 7.3a for tips on where to find data.

- **Refilling/servicing of equipment**

When existing equipment is being serviced and refilled with HFC, this will add to the bank. If data on servicing is difficult to obtain, a way of quantifying the amount used for this purpose is to assume it to be equal to the amount of chemicals emitted from operating equipment the previous year, taking into account that it should not exceed the amount of HFCs available in bulk. Another way to estimate the amount of HFCs used for servicing and refilling of equipment is to assume that it equals the estimated domestic sales minus the amount used for filling of new equipment.

Flow of HFCs out of the bank

HFC will mainly leave the bank through two processes: Emissions from the bank and through retired equipment.

- **Emissions during equipment lifetime**

Leakage of HFC from equipment in use, and hence emissions to the atmosphere, will remove chemicals from the bank. In the emission factor approach, this amount is estimated by applying an average emission factor per sub-application of equipment to the corresponding amount in the bank (equation 7.13). See Table 7.9 for default emission factors if national factors are not available. Note that the emission factors in Table 7.9 encompass annual leakage rates as well as emissions during service.

- **Retired equipment**

HFCs will also be removed from the bank when equipment is retired and scrapped or exported. Recycled HFC in the country will remain in the bank. The amount of HFCs in retired equipment is normally estimated based on average charge and the share of chemical remaining according to Table 7.9 and equation 7.14.

The fate of the HFCs contained in the retired equipment will also need to be quantified, often by a combination of data collection, assumptions and emission factors. It can be reclaimed and reused, destroyed or emitted. The used equipment containing HFC can also be exported to other countries. See "Calculation example for 2F1 (Tier 2)" for a more detailed description of the possible fates/flows and how to quantify them.

BOX 7.2C (NEW)
HOW TO BUILD THE BANK OF HFC

As described in Box 7.2B, it is essential to know the contents and structure of the bank of HFCs in order to estimate the emissions. In many cases this means that you need to quantify the bank from the year when HFCs were first used in a country up to the current year. There are two common ways of building the bank and the development back in time:

1. Collecting historic data on domestic sales and flows of HFCs, starting at bank=0

If data on domestic sales for all years since the HFCs were first introduced is available, this can be used to move forward from zero to the current bank by tracking the flow of chemicals into and out of the bank every year. This methodology is described in Box 7.2b.

2. Counting the number of equipment currently in place and interpolate back to bank=0

An alternative way of estimating the bank is to count the number of equipment units currently in place in a country and combine this with the average amount and type of HFCs contained in each type of equipment. This will provide an estimate of the current bank.

The historic development of the bank can be estimated by interpolation, i.e. filling in the holes in the time series between the year of introduction of HFC to the current situation (current amount in the bank). Refer to Volume 1, Chapter 5 for information on interpolation and other splicing techniques.

The following information on each of the relevant sub-applications need to be collected:

- The number of equipment units currently installed
- The average amount and type of HFC contained in each type of equipment
- The year of introduction, i.e. when HFC were first used in this kind of equipment in the country

Box 7.3a holds information on relevant data sources. For instance, the numbers of some kinds of equipment, like cars, might be available from national statistics or from a national register used for taxation. Industrial organizations often have statistics on mass-produced types of equipment, like numbers of household refrigerators, small air conditioning units, heat pumps and cars. If not, they might help you to estimate the sizes of markets, and hence consumption.

It is often challenging to get information on the number of large refrigeration and air conditioning systems. You might need to estimate this using information on the number of, for instance, large office buildings, hospitals, universities etc. in your country. Then you need to combine this with information on the typical number and types of air conditioning units per building. Again, industrial associations can often be helpful in getting this sort of information.

You need to collect information on the year each relevant kind of ODS-substitute was first used in each relevant type of equipment (sub-application) in your country (for instance, the year HFC-134a was first used in mobile air conditioning in your country). If this information is not available, you can make reasonable assumptions based on, for example, the ODS phase-out schedule in your country and/or substitution patterns in countries similar to yours.

Then, choose a method to fill in the years between year 0 and the current year. If you have no information on the development of the bank, a simple linear interpolation should be used. Otherwise, if some kind of information on the development is available, like the annual growth in sales of cars with air conditioning, this data can be used to model the bank year by year.

7.5.2.2 CHOICE OF EMISSION FACTORS

Tier 1a/b method

As explained within Section 7.5.2.1, Choice of Method, a composite emission factor is required to complete a Tier 1 method. Since the sub-applications within the refrigeration and air conditioning application are relatively heterogeneous, the validity of any single composite emission factor must be in doubt unless it takes into consideration the particular mix of sub-applications in the country. It is therefore *good practice* to develop composite emission factors on the basis of research within the country. The over-arching default emissions factor of 15 percent of the bank annually is used in the example of spreadsheet calculation, available at the IPCC web site: <https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol3.html>.

Tier 2a method

Good practice for choosing emission factors is to use country-specific data, based on information provided by equipment manufacturers, service providers, disposal companies, and independent studies. When national data are unavailable, inventory compilers should use the default emission factors shown in Table 7.9, Default Estimates for Charge, Lifetime and Emission Factors, which summarises best estimates of equipment charge, lifetime, emission factors during useful life, and parameters for end-of-life emissions. If data used to calculate the refrigerant bank cannot be broken down into the sub-applications as in Table 7.9, it is *good practice* to divide the bank by type of equipment using expert judgement, and calculate composite emission factors weighted according to that relative share, as described for Tier 1a/b.

Since the 2006 IPCC Guidelines were published, only a few new studies on leakage rates from stationary refrigeration and AC and mobile AC for some developed countries or regions have been published. The studies covering stationary refrigeration and AC indicate that the default values in Table 7.9 are still valid and thus are retained. For mobile AC, Table 7.9 is updated to include separate information on charge and annual emission factor during operating lifetime for maritime, railways, busses and other mobile ACs, based on Schwarz and Rhiemeier (2007) and Gallagher et al (2014).

The values in Table 7.9 are provided as ranges rather than point estimates. Inventory compilers should choose from the range according to country-specific conditions and document the reasons for their choices. The lower end of the lifetime and emission factor ranges is expected to be applicable to developed countries and to countries that have a mandatory or voluntary system in place to limit emissions during equipment service and use. The upper end of each range is expected to be applicable to developing countries without systems for limiting emissions.

Studies of emission rates in Japan for 2008 (Nomura Research Institute, Ltd, 2012), California for 2008 (Gallagher, et. al., 2014) and Germany for 2009-2013 (Umweltbundesamt, 2015) confirmed that the average emission factors in these countries were close to the lower range for most sub-application categories within the application area of Stationary Refrigeration and Air Conditioning. These factors are given in Table 7A.1-7A.3 in Annex 7A.1 and are intended to serve as examples of emission rates for developed countries. Only countries with similar systems and regulations or incentives in place should consider using these factors for relevant years.

For mobile air conditioning, emissions can occur during the useful life and during and after disposal of the equipment. Emission sources during the useful life include regular leaks (e.g. from seals), irregular leaks (e.g. due to accidents), and emissions during service (maintenance and refilling). The share of emissions from irregular leaks can be particularly large from passenger cars compared to other mobile vehicles as they are more likely to end up in accidents leading to eruption of the AC system. The default ranges in Table 7.9 encompass emissions from all stages. Several newer studies indicate that annual emission rates for modern passenger cars may be lower than the default lifetime emission factor lower range, e.g. see Schwarz and Harnisch (2003), Japan Automobile Manufacturers Association (2008), Papasavva *et al.* (2009), Clodic *et al.* (2011), Kim and Kim (2014), and Minnesota Pollution Control Agency (2017). However, in most of the studies, the presented emission rates include only regular leaks, or only regular and irregular leaks, excluding emissions during servicing. It is *good practice* to include emissions from all three sources when choosing operating lifetime emission factors.

There are few studies on remaining charge of refrigerants at end-of-life (p) and recovery efficiency (n_{rec}) in equipment, e.g. Kim and Kim (2014), Wimberger (2010), Schwarz (2012), Gallagher, et. al. (2014).

As the practice for mobile A/C service and disposal procedures may vary considerably between countries and over time, inventory compilers should investigate the national circumstances when developing country-specific factors for emissions and recovery efficiency. In some countries, A/C RRR service units (recover/recycle/recharge) are used to significantly reduce emissions at the service and disposal lifecycle stages. This will decrease emission factors during use and increase recovery efficiency (n_{rec}) at end of life. Some

countries have started to require recovery of refrigerants at the end-of-life, in which case the recovery efficiency could be higher than the suggested ranges in Table 7.9.

It is *good practise* to consider applying different emission factors in different years to reflect improvements in service and disposal practices and in equipment design and materials. Changes in emission factors over time could also be appropriate for countries that have introduced mandatory periodical inspection and repair regulations/schemes or similar incentives.

Some import and export of used vehicles and end-of-life vehicles occurs between countries (mostly from developed countries to developing countries). It is important for inventory compilers to take into account such flows of MAC equipment when estimating emissions from MAC as it may affect the composition of vehicle stock at various emission stages (lifetime and end-of-life).

Sub-application	Charge (kg)	Lifetimes (years) ²	Emission Factors (% of initial charge/year) ³		End-of-Life Emission (%)	
			(k)	(x)	($\eta_{rec,d}$)	(p)
Factor in Equation	(M)	(d)	At Time of Charge	Annual loss, Operating Lifetime	Recovery Efficiency ⁴	Initial Charge Remaining
Domestic Refrigeration	$0.05 \leq M \leq 0.5$	$12 \leq d \leq 20$	$0.2 \leq k \leq 1$	$0.1 \leq x \leq 0.5$	$0 < \eta_{rec,d} < 70$	$0 < p < 80$
Stand-alone Commercial Applications	$0.2 \leq M \leq 6$	$10 \leq d \leq 15$	$0.5 \leq k \leq 3$	$1 \leq x \leq 15$	$0 < \eta_{rec,d} < 70$	$0 < p < 80$
Medium & Large Commercial Refrigeration	$50 \leq M \leq 2000$	$7 \leq d \leq 15$	$0.5 \leq k \leq 3$	$10 \leq x \leq 35$	$0 < \eta_{rec,d} < 70$	$50 < p < 100$
Transport Refrigeration	$3 \leq M \leq 8$	$6 \leq d \leq 9$	$0.2 \leq k \leq 1$	$15 \leq x \leq 50$	$0 < \eta_{rec,d} < 70$	$0 < p < 50$
Industrial Refrigeration including Food Processing and Cold Storage	$10 \leq M \leq 10,000$	$15 \leq d \leq 30$	$0.5 \leq k \leq 3$	$7 \leq x \leq 25$	$0 < \eta_{rec,d} < 90$	$50 < p < 100$
Chillers	$10 \leq M \leq 2000$	$15 \leq d \leq 30$	$0.2 \leq k \leq 1$	$2 \leq x \leq 15$	$0 < \eta_{rec,d} < 95$	$80 < p < 100$
Residential and Commercial A/C, including Heat Pumps	$0.5 \leq M \leq 100$	$10 \leq d \leq 20$	$0.2 \leq k \leq 1$	$1 \leq x \leq 10$	$0 < \eta_{rec,d} < 80$	$0 < p < 80$
Mobile A/C	$5 \leq M \leq 6500$ (maritime) $10 \leq M \leq 30$ (railway) $4 \leq M \leq 18$ (busses) $0.5 \leq M \leq 2$ (other MAC)	$9 \leq d \leq 16$	$0.2 \leq k \leq 0.5$	$20 \leq x \leq 40$ (maritime) $5 \leq x \leq 20$ (railway) $10 \leq x \leq 20$ (other MAC)	$0 < \eta_{rec,d} < 50$	$0 < p < 50$

Source:

¹ UNEP RTOC Reports (UNEP-RTOC, 1999; UNEP-RTOC, 2003), Japan Refrigeration and Air Conditioning Industry Association (2009), Gallagher et al (2014), Umweltbundesamt (2015). For information on mobile A/C charge and mobile A/C emission factors for annual loss during operating lifetime: Schwarz and Rhiemeier (2007) and Gallagher et al (2014).

^{2,3} Lower value for developed countries and higher value for developing countries

⁴ The lower threshold (0%) highlights that there is no recovery in some countries.

7.5.2.3 CHOICE OF ACTIVITY DATA

Tier 1a/b method

Inventory compilers in countries that manufacture refrigerant chemicals should estimate Annual Sales of New Refrigerant using information provided by chemical manufacturers. Data on imported chemical should be collected from customs statistics, importers, or distributors.

Total Charge of New Equipment can be estimated using either:

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

Ensure this information only includes sales as refrigerant, not feedstock or other uses. The difference between the total sales of new refrigerant and that charged in new equipment is assumed to be used for servicing. Where information on new equipment charges is unavailable, it can be assumed that, in a mature market, two thirds of refrigerant is used for servicing while one third is used for new equipment. However, the adoption of such assumptions must be accompanied by some justification about the state of the market and how well these assumptions are likely to apply.

Tier 2 methods

Both Tier 2a and Tier 2b methods require the development of a matrix for each sub-application based on equipment type on the one hand and refrigerant type on the other hand. In order to derive the number of pieces of equipment for all the vintages, historic net consumption activity data is also required. The annual update of the matrix makes it possible to recalculate all emission types as detailed in Equations 7.10 to 7.14 each year. Moreover, the refrigerant choice has to be assessed on a year-by-year basis owing to changing national regulations (often relating to CFC and HCFC phase-out at different dates) and changing technological choices. In some countries HFC refrigerant regulations have started to enter into force.

Where country-specific data cannot be analysed to this level, globally or regionally validated activity data can be obtained from reputable databases based on refrigerant charges and lifetimes provided in Table 7.9, for all sub-applications, to facilitate Tier 2 methods. A number of refinements are usually necessary dependent on the particular circumstances of the country. Assistance for this can be obtained from application experts.

Other shared issues

Whether collecting country-specific activity data in support of a Tier 1 or a Tier 2 method, inventory compilers must take care in dealing with refrigerant blends. Table 7.8 illustrates the complexity already existing and blends are only expected to increase in popularity as manufacturers of equipment seek for further improvements in performance, particularly in respect of energy efficiency. Where blends contain both HFCs and other components, only the reportable elements need to be considered. This is even the case for other components with significant GWPs (e.g., CFCs and HCFCs).

Inventory compilers also need to consider how to monitor the movement of trade in equipment and products containing HFCs and/or PFCs. The Box 7.3 below sets out some of the measures required to estimate imports and exports adequately.

BOX 7.3

ACCOUNTING FOR IMPORTS AND EXPORTS OF REFRIGERANT AND EQUIPMENT

In estimating *Annual Sales of New Refrigerant*, *Total Charge of New Equipment*, and *Original Total Charge of Retiring Equipment*, as required for Tier 2b, inventory compilers should account for imports and exports of both chemicals and equipment. This will ensure that they capture the actual domestic consumption of chemicals and equipment. For example, if a country imports a significant share of the HFC-134a that it uses, the imported quantity should be counted as part of **Annual Sales**. Alternatively, if a country charges and then exports a significant number of household refrigerators, the total charge of the exported refrigerators should be subtracted from the total charge of the household refrigerators manufactured in the country to obtain **Total Charge of New Equipment**.

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

$$\begin{aligned} \text{Annual Sales} &= \text{Domestically Manufactured Chemical} \\ &+ \text{Imported Bulk Chemical} \\ &- \text{Exported Bulk Chemical} \\ &+ \text{Chemical Contained in Factory-Charged Imported Equipment} \\ &- \text{Chemical Contained in Factory-Charged Exported Equipment} \end{aligned}$$

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

$$\begin{aligned} \text{Total Charge of New Equipment} &= \text{Chemical to Charge Domestically Manufactured Equipment that} \\ &\quad \text{is not Factory-Charged} \\ &+ \text{Chemical to Charge Domestically Manufactured Equipment that is} \\ &\quad \text{Factory-Charged} \\ &+ \text{Chemical to Charge Imported Equipment that is not Factory-Charged} \\ &+ \text{Chemical Contained in Factory-Charged Imported Equipment} \\ &- \text{Chemical Contained in Factory-Charged Exported Equipment} \end{aligned}$$

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

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

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

$$\begin{aligned} \text{Annual Sales} &= \text{Domestically Manufactured Chemicals} \\ &+ \text{Imported Bulk Chemicals} \\ &- \text{Exported Bulk Chemicals} \end{aligned}$$

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

$$\begin{aligned} \text{Total Charge of New Equipment} &= \text{Chemicals to Charge Domestically Manufactured Equipment} \\ &+ \text{Chemical to Charge Imported Equipment that is not Factory-Charged} \end{aligned}$$

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

BOX 7.3A (NEW)**COMMON DATA SOURCES FOR THE HFC INVENTORY**

This box provides a short description of common data sources for the HFC inventory, complementing Table 7.10 in the *2006 IPCC Guidelines*. Examples of data are production, imports, exports and destruction of HFC and equipment containing HFC. Numbers of equipment units and growth rates in sales are also data commonly collected.

Governmental reports

Most countries have collected data for Refrigerant Management Plans (RMPs) or HCFC Phase-out Management Plans (HPMPs) through ODS-alternatives surveys. The consumption data generally contain information on:

- total past consumption of CFCs, and total current and past consumption of HCFCs and possibly also HFCs. Data on ODS are often given in ODP tonnes, which can be converted into metric tonnes using the substance-specific ODP values;
- sector-specific consumption of HCFCs and possibly also HFCs (e.g. amounts used in air conditioning, refrigeration, fire extinguishers, aerosols etc.);
- breakdown of HCFCs according to their use at each lifecycle stage such as manufacturing/assembly (initial charge) or servicing (refill)

Some countries have begun monitoring HFC consumption due to the inclusion of HFCs in the Montreal protocol. Countries that have ratified the Kigali amendment to the Montreal Protocol will be required to report consumption data on HFCs (production, import and export) annually.

European Member States report annually to the European Commission on production and imports of HFCs in bulk, in line with the EU F-Gas Regulation.

Surveys

There is often a limited number of companies producing, importing and exporting HFC in bulk; hence a way to obtain high quality data is to ask the producers, importers, and exporters for information. They should be able to provide information on the amount of gas they produce, import, or export in a certain year. In addition, they may be able to indicate the equipment types in which each HFC or blend is used.

The number of companies importing equipment containing HFC can be large, and surveying this might be resource intensive. If this is the case, other data sources such as sales statistics or national customs registers (see below) may be used instead.

Surveys can also be a way to obtain information on HFC from end-users. Generally, this requires good knowledge of the market and preparatory market research may be needed before launching a survey.

Surveys can also be a way to discover areas and applications previously unknown to the inventory compilers.

National Customs Registers

National Customs Registers contain information on imports and exports of chemicals and equipment potentially containing HFC. If the HFC are subject to tax, such a register might provide the amounts of refrigerant contained in the products. If not, it will probably be necessary to make assumptions regarding the identities and amounts (charge sizes) of HFCs in different types of equipment, multiplying the charge size by the number of equipment units of each type to obtain the total amount of that HFC imported.

BOX 7.3A (NEW) (CONTINUED)
COMMON DATA SOURCES FOR THE HFC INVENTORY

Other national registers

Many countries have national registers of cars uses for taxation purposes. This data source might provide figures on the number of cars, and possibly other information like age and size.

National Product Register/European Chemical Agency: In some countries, a national Products Register is used to store information on chemical products (including HFC) that are manufactured in or transferred or imported into the country and information on the ways in which these are being used.

Industrial organizations

Industrial organizations or trade associations often have statistics on mass-produced types of equipment, like numbers of household refrigerators, small air conditioning units, heat pumps and cars.

If not, they might help with assessments of the size of markets, and hence the consumption figures. It is often challenging to get information on the number of large refrigeration and air conditioning systems. Industrial organizations might provide useful information like annual growth in sales of equipment and average charge size of various types of equipment.

National statistics

Many countries have national offices publishing annual statistics with useful information, like the stock of vehicles and buildings (number or area by type of building), or production of commodities.

7.5.2.4 APPLYING TIER 2 METHODS – THE EXAMPLE OF MOBILE AIR CONDITIONING (MAC)

The Box 7.4 below sets out the step-by-step approach required to assess the emissions from the mobile air conditioning sub-application of a hypothetical country's inventory. The method adopted is primarily a Tier 2a approach, although there are also elements which would be equally applicable to Tier 2b. This example, therefore, highlights the reality that pure approaches and methods are rare in practice. There will often be a mix of emission-factor approach and mass-balance approach as well as a mix of country-specific data and globally or regionally derived data. As pointed out in Section 7.1.2.1, one method, approach or dataset will often be used to cross-check another. This example also demonstrates that a detailed implementation of the Tier 2a method requires a significant amount information gathering about a sub-application. Once established, it is less burdensome to implement the approach in subsequent years. Also note that assumptions made are for example only; inventory compilers should collect country-specific information rather than using the assumptions shown.

BOX 7.4 (UPDATED)**EXAMPLE OF THE APPLICATION OF A TIER 2A CALCULATION FOR MOBILE AIR CONDITIONING****Introduction**

National inventories and other studies to date show that emissions of HFC-134a from mobile air conditioners (MACs) contribute significantly to the Refrigeration and Air Conditioning (RAC) Application emissions and the ODS Substitutes Category emissions. For many countries, emissions from MACs will comprise 50 percent or more of the RAC emissions and possibly more than 50 percent of the total ODS Substitutes Category emissions. This is due to many factors, including:

- The phaseout of ODSs to HFCs in MACs occurred earlier and more quickly than other Sub-Applications, such as residential (stationary) air conditioning and commercial refrigeration (supermarkets), which still rely substantially on ODSs.
- MACs are subject to extremes in terms of physical shock and vibration and hence emissions tend to be large.
- The lifetime of MACs tends to be shorter than many other RAC Sub-Applications, so that end-of-life emissions are seen earlier and equipment stocks relying on ODSs are replaced sooner with HFCs.
- Due to the small charge of refrigerant involved, recovery from MACs is often seen as uneconomical and hence is not often practiced during service and disposal.

In addition, data on vehicle purchases and registrations in a country are often known to a higher degree of quality or are easily obtained. Hence, it is *good practice* to estimate emissions from this Sub-Application. The following text describes how the general equations for the RAC Application can be applied to the MAC Sub-Application.

Data Gathering and Assumptions

An accurate estimate of MAC emissions may be obtained by collecting some data at the Sub-Application level and applying a few basic assumptions to simplify the data and calculations required, as follows:

Refrigerant Type. It will be important to separate each data point by refrigerant, so that emissions of each refrigerant are calculated separately. For MACs, this may be simplified by the fact that all MACs produced since the mid- to late-1990s use HFC-134a as the refrigerant. However, CFC-12 was used in the past and still exists in some operating systems. Furthermore, for the future other refrigerants such as HFC-152a and R-744 (carbon dioxide) are being considered.

Refrigerant Sold in Containers (RM_t). For MACs, refrigerant generally comes in three basic types of containers – ‘bulk containers’ sent to vehicle manufacturers to fill new MACs, ‘small cans’ containing about 300-500 grams of refrigerant generally used by individuals servicing their own equipment, and ‘cylinders’ containing about 10-15 kilograms of refrigerant used by shops that service many vehicles. If one assumes no losses from bulk containers (see below), then in order to calculate $E_{\text{containers}}$, one needs to know the total refrigerant sold in small cans (RM_{sc}) and cylinders (RM_{cy}). It will be important to distinguish the refrigerant sold into different Sub-Applications (e.g., HFC-134a is also used in the chillers and domestic refrigeration Sub-Applications) so that only the refrigerant sold for MACs is used in the calculations. This data may be obtained from small can packagers and refrigerant producers/distributors.

Container Heels (c). For this example, we assume the heels from service containers are not recovered (e.g., the cylinders are discarded, not reused) and are $c_{sc} = 20$ percent for the small can and $c_{cy} = 2$ percent for the cylinder. Because bulk refrigerant containers generally go back to the refrigerant producer and are refilled, we can assume there are no heels that would be emitted and hence $c_{\text{bulk}} = 0$ percent.

BOX 7.4 (UPDATED) (CONTINUED)

EXAMPLE OF THE APPLICATION OF A TIER 2A CALCULATION FOR MOBILE AIR CONDITIONING

MACs Produced Each Year (N_t). If the number of MACs placed in service each year is not known, an estimate can be made by multiplying the number of cars placed in service each year by an estimate of the percentage that were sold with MACs. These data may be available from automobile manufacturers, MAC producers/suppliers, or government agencies involved in transportation, infrastructure and highway safety. If more than one type of refrigerant is used, it is important to separate each N_t into the different refrigerants, e.g., $N_{1994} = N_{1994,CFC-12} + N_{1994,HFC-134a}$.

Nominal Charge of Each MAC (m_t). This factor would likely vary by the type of vehicle; for instance small passenger cars will likely have lower refrigerant charges than buses or larger cars, especially those with multiple evaporators. Likewise, this could vary over time, for instance decreasing as manufacturers make smaller systems for the same vehicle size, or increasing as larger cars and more multiple-evaporator units enter the market. For this example, we assume a constant over time at an average $m = 0.7$ kg, which is typical of small to medium-sized passenger cars.

Refrigerant Charged into New Equipment (M_t). This is easily calculated as $M_t = N_t \cdot m_t = 0.7 \cdot N_t$.

Assembly Losses (k). This is used to calculate the Charge Emissions, also referred to as 'First-Fill Emissions.' The loss rate is often small, on the order of $k = 0.5$ percent or smaller. For simplicity, we assume $k = 0$ in this example.

Lifetime (d). The presumed lifetime of a MAC. This variable can be based on national data and can be different for different types of MACs (passenger cars, buses, etc.) For this example, we assume the lifetime of all MACs is $d = 12$ years.

Bank in Existing Equipment (B). The bank will be the amount of refrigerant in MACs put into service, minus the amount of refrigerant in MACs disposed, plus the amount of refrigerant used to service MACs, minus the amount that has leaked. In actuality, a given MAC will probably leak over several years before being serviced. Rather than attempting to account for this, for this example we apply Equation 7.13 which assumes all MACs are serviced each year such that the estimated charge of each MAC is the same as the nominal charge. The annual emission rate is averaged to account for this assumption. This will only produce small errors unless the year-to-year sales of MACs fluctuate widely. Hence the bank in any given year is the sum of the Refrigerant Charged into New Equipment each year from the current year back to the assumed average lifetime of the equipment. Thus,

$$B_t = \sum_{i=1}^d M_{t-i+1}$$

For example, using $d = 12$ years, the bank in 2006 would be $B_{2006} = M_{2006} + M_{2005} + M_{2004} + \dots + M_{1997} + M_{1996} + M_{1995}$.

Annual Emission Rate (x). This factor accounts for both leaks from equipment as well as any emissions during service. Both of these items can be different for different types of MACs and can also vary by when the MAC was produced (i.e., older MACs may leak more than newer MACs). If annual servicing does not occur, the amount emitted at any servicing event needs to be average over the number of years between servicing event to obtain the annual rate. This amount is likely to vary considerably depending on national conditions and what type(s) of service is (are) performed. Whether recovery of the given charge before service is performed must be considered, and may be deduced in part by examining the amount of refrigerant sold in small cans versus cylinders. For this example, we assume that 15 percent of the nominal charge is leaked each year and 5 percent on average is emitted during servicing. Hence, $x = 20$ percent.

Residual Charge in MACs Disposed (p). Assuming that the MAC is serviced the year before it is disposed, and that the annual nominal charge is estimated, this is easily calculated as $p = 1 - \text{nominal charge}$. In our example, $p = 1 - 15\% = 0.85$.

BOX 7.4 (UPDATED) (CONTINUED)**EXAMPLE OF THE APPLICATION OF A TIER 2A CALCULATION FOR MOBILE AIR CONDITIONING**

Recovery Efficiency (nrec). If no regulations or incentives exist to require recovery of refrigerant from MACs disposed, then likely very little will occur. So, for this example, we assume that $nrec = 0$.

Calculation of Different Types of Emissions

Now that these data have been gathered and assumptions have been made, calculating the emissions may be performed. An example for year $t = 2006$ follows:

Container Emissions (Equation 7.11).

$$E_{containers,2006} = RM_{cy,2006} \cdot c_{cy} + RM_{sc,2006} \cdot c_{sc} = 0.02 \cdot RM_{cy,2006} + 0.2 \cdot RM_{sc,2006}$$

Charging Emissions (Equation 7.11).

$$E_{charge,2006} = M_{2006} \cdot k = 0$$

Lifetime (Operating and Servicing) Emissions (Equation 7.13).

$$\begin{aligned} E_{operation,2006} &= B_{2006} \cdot x = 0.20 \cdot B_{2006} = 0.20 \cdot \sum_{i=1}^d M_{t-i+1} \\ &= 0.20 \cdot (M_{2006} + M_{2005} + M_{2004} + \dots + M_{1997} + M_{1996} + M_{1995}) \\ &= 0.20 \cdot m \cdot (N_{2006} + N_{2005} + N_{2004} + \dots + N_{1997} + N_{1996} + N_{1995}) \\ &= 0.20 \cdot 0.7 \cdot (N_{2006} + N_{2005} + N_{2004} + \dots + N_{1997} + N_{1996} + N_{1995}) \\ &= 0.14 \cdot (N_{2006} + N_{2005} + N_{2004} + \dots + N_{1997} + N_{1996} + N_{1995}) \end{aligned}$$

End-of-Life Emissions (Equation 7.14).

$$\begin{aligned} E_{end-of-life,2006} &= M_{2006-d} \cdot p \cdot (1 - n_{rec}) = M_{2006-12} \cdot 0.85 \cdot (1 - 0) \\ &= 0.85 \cdot M_{1994} = 0.85 \cdot 0.7 \cdot N_{1994} = 0.595 \cdot N_{1994} \end{aligned}$$

Calculation of Total Emissions

Total MAC Emissions (Equation 7.10).

$$\begin{aligned} E_{total,2006} &= E_{containers,2006} + E_{charge,2006} + E_{lifetime,2006} + E_{servicing,2006} + E_{end-of-life,2006} \\ &= 0.02 \cdot RM_{cy,2006} + 0.2 \cdot RM_{sc,2006} + 0 \\ &\quad + 0.14 \cdot (N_{2006} + N_{2005} + N_{2004} + \dots + N_{1997} + N_{1996} + N_{1995}) + 0.595 \cdot N_{1994} \\ &= 0.02 \cdot RM_{cy,2006} + 0.2 \cdot RM_{sc,2006} \\ &\quad + 0.14 \cdot (N_{2006} + N_{2005} + N_{2004} + \dots + N_{1997} + N_{1996} + N_{1995}) + 0.595 \cdot N_{1994} \end{aligned}$$

The only unknowns are:

- RM_{sc} – refrigerant (in kilograms) sold in small cans to service MACs, which may be obtained from small can packagers;
- RM_{cy} – refrigerant (in kilograms) sold in cylinders to service MACs, which may be obtained from refrigerant producers/distributors; and,
- N_t – the number of MACs put in service each year, which may be available from automobile manufacturers, MAC producers/suppliers, or government agencies involved in transportation, infrastructure and highway safety.

BOX 7.4 (UPDATED) (CONTINUED)

EXAMPLE OF THE APPLICATION OF A TIER 2A CALCULATION FOR MOBILE AIR CONDITIONING

If the emissions from refrigerant containers and from end-of-life are not included, for example if it is believed that service cylinders are completely evacuated and minimal MACs reach their end-of-life in the given year, this equation becomes simply an activity (the number of MACs) multiplied by an emission factor (annual emission rate times average charge size, in this case 0.14 kg per MAC). This calculation yields the total emissions in kilograms of refrigerant. Keeping each refrigerant separate and multiplying each sum by the refrigerant's GWP will yield kilograms of CO₂ equivalent emissions. Dividing by 1 billion (10⁹) will yield emissions in teragrams of CO₂ equivalent (TgCO₂eq).

7.5.2.5 COMPLETENESS

No refinement.

7.5.2.6 DEVELOPING A CONSISTENT TIME SERIES

No refinement.

7.5.3 Uncertainty assessment

No refinement.

7.5.4 Quality Assurance/Quality Control (QA/QC), Reporting and Documentation

No refinement.

7.6 FIRE PROTECTION

No refinement.

7.7 OTHER APPLICATIONS

No refinement.

Annex 7A.1 (New) Examples of national studies on emission rates for stationary refrigeration and air-conditioning systems

The three sets of emission factors presented below are intended to serve as examples of emission rates (and in one case recovery efficiency at end-of-life) for stationary refrigeration and air-conditioning systems. Only countries with similar systems and regulations or incentives in place should consider using these factors for relevant years. In each table, the IPCC sub-application (found in Table 7.9) are amended for the purpose of reference.

Equipment Type or Emission Sub-application	Annual loss, Operating Lifetime Emission Factors (% of initial charge/year)	Recovery Efficiency, End-of-Life Emission (%)	IPCC Sub-application
Factor in Equation	(x)	(nrec,d)	
Refrigeration Large Centralized System ≥ 907.2 kg (2,000 lbs.)	21.0%	80%	Medium & Large Commercial Refrigeration
Refrigeration Medium Centralized System $90.7 < 907.2$ kg (200- < 2,000 lbs.)	15.0%	80%	Medium & Large Commercial Refrigeration
AC Large Centrifugal Chiller ≥ 907.2 kg (2,000 lbs.)	2.4%	80%	Chillers
AC Medium Centrifugal Chiller $90.7 < 907.2$ kg (200- < 2,000 lbs.)	1.4%	80%	Chillers
AC Chiller - Packaged $90.7 < 907.2$ kg (200- < 2,000 lbs.)	6.9%	80%	Chillers
Refrigeration Large Cold Storage ≥ 907.2 kg (2,000 lbs.)	21.6%	84%	Industrial Refrigeration including Food processing and Cold Storage
Refrigeration Medium Cold Storage $90.7 < 907.2$ kg (200- < 2,000 lbs.)	28.8%	84%	Industrial Refrigeration including Food processing and Cold Storage
Refrigeration Process Cooling ≥ 907.2 kg (2,000 lbs.)	6.8%	80%	Industrial Refrigeration including Food processing and Cold Storage
Refrigerated Condensing units $22.7 \leq 90.7$ kg ($50 \leq 200$ lbs.)	14.5%	80%	Medium & Large Commercial Refrigeration
Unitary AC $22.7 \leq 90.7$ kg ($50 \leq 200$ lbs.)	11.3%	80%	Residential and Commercial A/C, including Heat Pumps
Refrigerated Condensing Units ≤ 22.7 kg (50-lbs. or less)	15%	66%	Medium & Large Commercial Refrigeration
Unitary A/C ≤ 22.7 kg (50-lbs. or less) (central)	10%	44%	Residential and Commercial A/C, including Heat Pumps
Unitary A/C ≤ 22.7 kg (50-lbs. or less) (window unit)	2%	0%	Residential and Commercial A/C, including Heat Pumps

TABLE 7A.1 (NEW) (CONTINUED)			
CALIFORNIA STUDY FOR 2008: EMISSION FACTORS FOR STATIONARY REFRIGERATION AND AIR-CONDITIONING SYSTEMS			
Equipment Type or Emission Sub-application	Annual loss, Operating Lifetime Emission Factors (% of initial charge/year)	Recovery Efficiency, End-of-Life Emission (%)	IPCC Sub-application
Factor in Equation	(x)	(nrec,d)	
Residential Appliance (refrigerator-freezer)	1%	33%	Domestic Refrigeration
Transport Refrigerated Units (TRUs)	18.3%	85%	Transport Refrigeration
Refrigerated Shipping Containers	5%	81%	Transport Refrigeration
Source: Gallagher et al (2014).			

Equipment Type or Emission Sub-application		Annual loss, Operating Lifetime Emission Factors (% of initial charge/year)	IPCC Sub-application
Factor in Equation		(x)	
Large Refrigerators-freezers	Centrifugal refrigerating machine	7%	Chillers
	Screw refrigerating machine	12%	Industrial Refrigeration including Food Processing and cold storage
Medium Refrigerators-freezers	Transport refrigerator-freezer unit	15%	Transport Refrigeration
	Refrigerator-freezer unit	17%	Medium&Large Commercial Refrigeration
	Condensing unit	13%	Medium&Large Commercial Refrigeration
	Separately placed showcase	16%	Medium&Large Commercial Refrigeration
Commercial air-conditioning equipment	PAC (Package air-conditioning) for store	3%	Residential and Commercial A/C, including Heat Pump
	PAC (Package air-conditioning) for building	3,5%	Residential and Commercial A/C, including Heat Pump
	PAC (Package air-conditioning) for industry	4,5%	Residential and Commercial A/C, including Heat Pump
	GHP	5,0%	Residential and Commercial A/C, including Heat Pump
Room air-conditioning		2%	Residential and Commercial A/C, including Heat Pump
Small Refrigerators-freezers	All-in-one type (e.g. built-in showcase, ice making machinery, water fountain, commercial refrigerator)	2%	Stand-alone Commercial Application
Chilling unit	Chilling unit (e.g. chilling unit for refrigerator-freezer, chilling unit for air-conditioning)	6%	Chillers

Source: Nomura Research Institute, Ltd. (2012).

TABLE 7A.3 (NEW) GERMAN STUDY FOR 2009-2013: EMISSION FACTORS FOR STATIONARY REFRIGERATION AND AIR-CONDITIONING SYSTEMS	
Equipment Type or Emission Sub-application	Annual loss, Operating Lifetime Emission Factors (% of initial charge/year)
Factor in Equation	(x)
Medium & Large Commercial Refrigeration (centralized)	7.64 – 10.02
Small Commercial Refrigeration (condensing units)	3.09 -5.18
Industrial Refrigeration including Food Processing and Cold Storage	4.71
AC Chiller	3.39
AC Multisplit/VRF (Variable Refrigerant Flow)	3.80
Source: Umweltbundesamt (2015)	

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