Review of the consistency of PM, HM and POP emission factors – 6C Waste Incineration

Waste incineration encompasses five chapters in the GB:

- 6Ca Clinical waste incineration
- 6Cb Industrial waste incineration
- 6Cc Municipal waste incineration
- 6Cd Cremation
- 6Ce Small scale waste burning

Cross-cutting observations

In general the EFs provided are rather old and are based on different references for different pollutants, thereby potentially compromising the consistency of the EFs. Furthermore, many of the EFs refer to the previous version of the GB, which is a dead end meaning that the EFs are in fact not referenced.

Several of the EF tables for both tier 1 and tier 2 are missing relevant pollutants, and for several EF tables only the sum of PAH is available as EF and not EFs for the four PAHs for which there is a reporting requirement.

Clinical waste incineration

The GB chapter contains tier 1 EFs and five tier 2 EF tables. There are no PM10 and PM25 EFs available in neither the tier 1 nor the tier 2 tables. Only a total PAH EF is available.

The difference between the tier 1 and the different tier 2 EFs is limited to the EFs of some of the heavy metals and PCDD/F. It has not been possible to acquire a copy of Wenborn et al. (1998), which is the reference for the difference in EFs of cadmium, mercury and lead.

Since the vast majority of EFs are either missing or the same for all EF tables, it seems unnecessary to have so many EF table for this source category. Since it has not been possible to source some of the key current references, it is proposed to completely reshape the chapter based on available literature data. Depending on the available data, it could mean that the number of EF tables will be significantly reduced.

It has not been possible to complete the literature survey at this stage, so the main issue at the TFEIP meeting is whether it would be acceptable to the TFEIP to simplify the EFs provided taking into account the issues mentioned above.

Industrial waste incineration

The GB currently contains tier 1 EFs and tier 2 EFs for uncontrolled incineration of industrial waste and for incineration of sludge from wastewater treatment.

Industrial waste incineration

The GB currently contains tier 1 EFs, which is a mix of EFs taken from the BREF document, the previous GB and the ESPREME project and tier 2 EFs for unabated industrial waste incineration. Most of the tier 2 EFs are referenced to a previous version of the GB, which states that the same EFs as for medical waste incineration has been used for most pollutants. However, this is incorrect.

The text prefacing the tier 1 EFs states that only particle abatement is assumed. However, when analysing the EFs for e.g. SO_2 and NO_x, it seems evident that the EFs must be for plants with both desulphurisation and NO_x abatement installed. The tier 1 EFs as presented for the most part seems to be tier 2 EFs for a plant using relatively modern flue gas cleaning devices. Therefore it should be considered to move the current tier 1 EFs to a tier 2 table indicating flue gas cleaning (desulphurisation, NO_x abatement and particle abatement). The unabated EFs could then be implemented as tier 1. Abatement efficiencies are included in the GB, so it will be possible for countries to take into account the actual abatement technologies used in the country.

Sludge incineration

The EFs currently in the GB refers to US EPA (1996) for main pollutants and PM, while other references are used for HM, PAH and PCDD/F.

It is not clear why other references have been chosen for the heavy metals since factors are available in the AP42 chapter on sewage sludge incineration (US EPA, 1995). For PAH EFs are available for single PAH from the US EPA (US EPA, 1998). From US EPA (1995) only the uncontrolled EFs are complete regarding pollutants. However, in US EPA (1998) the PAH EFs are provided for plants with wet scrubbers. The EFs have a rating of E and the ranges of the reported EFs are significant, therefore it is considered reasonable to include them in the EF table.

The HM EFs are rated B by the US EPA (C for mercury) and have been validated by an Australian study (Sullivan & Woods, 2000). Therefore, the HM EFs from the US EPA are considered to be the best data available.

For PCB and HCB the available data are also from North America.

Recommendations

It is proposed to use the available data in chapter 2.2 of AP42 from the US EPA and to supplement these with data from other sources for PAHs, PCBs and HCB. Based on this the EF table would be as presented below.

Tier 2 emission factors					
	Code	Name			
NFR source category	6.C.b	Industrial waste incineration			
Fuel	NA				
SNAP (if applicable)	090205	Incineration of sludge from waste water treatment			
Technologies/Practices					
Region or regional conditions					
Abatement technologies	Uncontrolled				
Not applicable	HCH				
Not estimated	NH3				
Pollutant	Value	Unit	95 % confidence interval		Reference
			Lower	Upper	
NOx	2,5	kg/Mg			US EPA, 1995
CO	15,5	kg/Mg			US EPA, 1995
NMVOC	0,84	kg/Mg			US EPA, 1995
SO2	14	kg/Mg			US EPA, 1995
TSP	52	kg/Mg			US EPA, 1995
PM10	4,1	kg/Mg			US EPA, 1995
PM2.5	1,1	kg/Mg			US EPA, 1995
Pb	50	g/Mg			US EPA, 1995
Cd	16	g/Mg			US EPA, 1995
Hg	2,3	g/Mg			US EPA, 1995
As	4,7	g/Mg			US EPA, 1995
Cr	14	g/Mg			US EPA, 1995

Cu	40	g/Mg			US EPA, 1995
Ni	8	g/Mg			US EPA, 1995
Se	0,15	g/Mg			US EPA, 1995
Zn	66	g/Mg			US EPA, 1995
PCBs	4,5	mg/Mg			US EPA, 1987
PCDD/F	4,65	mg/Mg			US EPA, 1995
Benzo(a)pyrene	0,51	mg/Mg			US EPA, 1998
Benzo(b)fluoranthene	0,07	mg/Mg			US EPA, 1998
Benzo(k)fluoranthene	0,61	mg/Mg			US EPA, 1998
Indeno(1,2,3-cd)pyrene	0,1	mg/Mg			US EPA, 1998
HCB	4,7	mg/Mg			Bailey, 2001

Municipal waste incineration

The chapter in the GB currently contains tier 1 and tier 2 EFs. The tier 2 EFs are reported as uncontrolled while the tier 1 EFs according to the text are based on plants with "acid gas abatement and particle abatement". The abatement efficiency for acid gas abatement is only listed as 76 %, which is very low compared to present day standards.

The EFs presented below are based on measurements carried out in Denmark (Nielsen et al., 2010) after the implementation of the EU waste incineration directive. The original EFs are based on energy input. The EFs have been converted using a NCV of 10.5 GJ per tonnes.

Tier 2 emission factors					
	Code	Name			
NFR source category	6.C.c	Municipal waste incineration			
Fuel	NA				
SNAP (if applicable)	090202	Incineration of domestic or municipal wastes			
Technologies/Practices					
Region or regional conditions					
Abatement technologies	Desulphurisation, NOx abatement (SNCR), particle abatement (ESP and/or FB), activated carbon				
Not applicable	HCH				
Not estimated					
Pollutant	Value	Unit	95 % confidence interval		Reference
			Lower	Upper	
NOx	1071	g/Mg			Nielsen et al., 2010
CO	41	g/Mg			Nielsen et al., 2010
NMVOC	5,9	g/Mg			Nielsen et al., 2010
SO2	87	g/Mg			Nielsen et al., 2010
NH3	3,0	g/Mg			Nielsen et al., 2010
TSP	3,0	g/Mg			Nielsen et al., 2010
PM10		g/Mg			
PM2.5		g/Mg			
Pb	58,0	mg/Mg			Nielsen et al., 2010
Cd	4,6	mg/Mg			Nielsen et al., 2010
Hg	18,8	mg/Mg			Nielsen et al., 2010
As	6,2	mg/Mg			Nielsen et al., 2010
Cr	16,4	mg/Mg			Nielsen et al., 2010
Cu	13,7	mg/Mg			Nielsen et al., 2010
Ni	21,6	mg/Mg			Nielsen et al., 2010
Se	11,7	mg/Mg			Nielsen et al., 2010
Zn	24,5	mg/Mg			Nielsen et al., 2010
PCBs	3,4	ng/Mg			Nielsen et al., 2010
PCDD/F	52,5	ng/Mg			Nielsen et al., 2010
Benzo(a)pyrene	8,4	mikrog/Mg			Nielsen et al., 2010
Benzo(b)fluoranthene	17,9	mikrog/Mg			Nielsen et al., 2010
Benzo(k)fluoranthene	9,5	mikrog/Mg			Nielsen et al., 2010
Indeno(1,2,3-cd)pyrene	11,6	mikrog/Mg			Nielsen et al., 2010
HCB	45,2	mikrog/Mg			Nielsen et al., 2010

These EFs can be assumed to be representative for modern waste incineration plants. The waste incineration plants in Denmark combusts a mix of municipal and commercial/industrial waste.

Recommendations

It is recommended to replace the current tier 1 EFs with the EFs presented above. Furthermore, it is recommended to keep the table with unabated EFs, and the table on abatement efficiencies for the time being. It is reasonable to revise these data in the future.

Cremation

The chapter on cremation contains tier 1 EFs for human cremations as presented below. Furthermore, there are tier 2PM EFs available for burning of cows and sheep.

Incineration of corpses

The current tier 1 EFs in the GB are shown below.

Table 3 1 Tier 1 emission factors for source category 6.C.d Cremation, cremation of human bodies

Tier 1 default emission factors					
	Code	Name			
NFR Source Category	6.C.d	Cremation			
Fuel	NA				
Not applicable	Aldrin, Chlordane, Chlordecone, Dieldrin, Endrin, Heptachlor, Heptabromo-biphenyl, Mirex, Toxaphene, HCH, DDT, PCB, PCP, SCCP				
Not estimated	NH3, PM10, PM2.5, Se, Zn, Benzo(b)fluoranthene, Benzo(k)fluoranthene, Indeno(1,2,3-cd)pyrene, Total 4 PAHs, HCB				
Pollutant	Value	Unit	95% confidence interval		Reference
			Lower	Upper	
NOx	0.309	kg/body	0.0309	3.09	EMEP Corinair Guidebook 2006
CO	0.141	kg/body	0.0141	1.41	EMEP Corinair Guidebook 2006
NMVOC	0.013	kg/body	0.0013	0.13	CANA (1993)
SOx	0.544	kg/body	0.0544	5.44	EMEP Corinair Guidebook 2006
TSP	14.6	g/body	9.63	19.3	Santarsiero (2005)
Pb	0.0186	mg/body	0.00186	0.186	EMEP Corinair Guidebook 2006
Cd	0.00311	mg/body	0.000311	0.0311	EMEP Corinair Guidebook 2006
Hg	0.934	mg/body	0.00934	93.4	EMEP Corinair Guidebook 2006
As	0.011	mg/body	0.0011	0.11	EMEP Corinair Guidebook 2006
Cr	0.00844	mg/body	0.000844	0.0844	EMEP Corinair Guidebook 2006
Cu	0.00771	mg/body	0.000771	0.0771	EMEP Corinair Guidebook 2006
Ni	0.0107	mg/body	0.00107	0.108	EMEP Corinair Guidebook 2006
PCDD/F	0.0168	µg/body	0.00037	80	EMEP Corinair Guidebook 2006
Benzo(a)pyrene	0.0103	µg/body	0.00103	0.103	EMEP Corinair Guidebook 2006

It can be seen that EFs are not estimated for a large number of pollutants. Furthermore, most of the EFs are referenced to the previous version of the GB.

The recommended EFs are shown below.

Tier 1 default emission factors					
	Code	Name			
NFR source category	6.C.d	Cremation			
Fuel	NA				
Not applicable	HCH, NH3				
Not estimated					
Pollutant	Value	Unit	95 % confidence interval		Reference
			Lower	Upper	
NO_x	0.309	kg/body	0.0309	3.09	Current GB
CO	0.141	kg/body	0.0141	1.41	Current GB
NMVOC	0.013	kg/body	0.0013	0.13	Current GB
SO_2	0.544	kg/body	0.0544	5.44	Current GB
TSP	38.56	g/body			WebFIRE
PM_{10}	34.70	g/body			WebFIRE
$PM_{2.5}$	34.70	g/body			WebFIRE
Pb	30.03	mg/body			WebFIRE

Cd	5.03	mg/body			WebFIRE
Hg	1492.32	mg/body			WebFIRE
As	13.61	mg/body			WebFIRE
Cr	13.56	mg/body			WebFIRE
Cu	12.43	mg/body			WebFIRE
Ni	17.33	mg/body			WebFIRE
Se	19.78	mg/body			WebFIRE
Zn	160.12	mg/body			WebFIRE
PCBs	0.41	mg/body			Toda, 2006
PCDD/F	0.027	µg/body			WebFIRE
Benzo(a)pyrene	13.20	µg/body			WebFIRE
Benzo(b)fluoranthene	7.21	µg/body			WebFIRE
Benzo(k)fluoranthene	6.44	µg/body			WebFIRE
Indeno(1,2,3-cd)pyrene	6.99	µg/body			WebFIRE
Total 4 PAHs	33.84	µg/body			WebFIRE
HCB	0.15	mg/body			Toda, 2006

SO_2, NO_x, NMVOC, CO

The following table provides an overview of the different sources to the emission factors for SO_2, NO_x, NMVOC and CO for human cremation. There is good agreement between the different sources, providing that the emission factors selected for the previous GB is a reasonable estimate. It is recommended that these four emission factors are not changed.

However, it should be noted that the emission factor for SO_2 has increased with a factor 10 from, GB2007 to GB2009. It has not been possible to find the original source to verify which factor is correct.

SO_2, NO_x, NMVOC, CO emission factors, kg/cremated body

	GB2009	US-EPA 1996*	CANA 1993*	OMINEA 2011	Sweitz IIR 2011	Norway IIR 2012	Santarsiero et al, 2005b	NPI crematoria, 2011
SO_2	5.44E-01	5.44E-02	6.36E-02	2.39E-01		1.81E-02	7.18E-02	7.39E-02
NO_x	3.09E-01	3.09E-01	4.55E-01	1.18	2.10E-01	4.41E-02	5.25E-01	5.22E-01
NMVOC	1.3E-02		1.30E-02	3.38E-02	1.80E-02	6.37E-02		
CO	1.41E-01	1.41E-01	2.12E-01	1.11E-01	2.25E-01	7.35E-01	8.93E-02	1.00E-01

*Sources provided by The Guidebook 2007

Particulate matter, heavy metals (except mercury)

The following table provides an overview of the different sources of the emission factors for particulate matter and heavy metals for human cremation.

When comparing to other sources, the GB values for the individual metals appears to be under estimated. It is recommended to use US EPA WebFIRE, which will also provide some of the previously not included compounds. By using WebFIRE as the source for both particles, individual heavy metals, PAHs and PCDD/F, a higher degree of consistency is achieved.

Data given by WebFIRE includes an average body weight of incinerated corpses of 141 lb (64 kg); wrapping material adds another 4 lb (1.8 kg) cardboard and 2 lb (0.9 kg) wood. The only calculation performed on the provided data is the conversion from pounds to kilograms; 1 lb, lbs = 0.453 592 kg. Data provided by WebFIRE refers to “Emissions Testing of a Propane Fired Incinerator at a Crematorium. October 29, 1992. (Confidential Report No. ERC-39)”

Particulate matter and heavy metals emission factors, kg/cremated body

	GB2009	US-EPA 1996*	CANA 1993*	OMINEA 2011	Sweitz IIR 2011	WebFIRE	Santarsiero et al, 2005b	NPI crematoria, 2011
TSP	1.46E-02	2.54E-05	2.24E-01	1.55	6.60E-02	3.86E-02	1.59E-01	
PM_{10}				1.40	5.90E-02	3.47E-02		
$PM_{2.5}$				1.24	5.90E-02	3.47E-02		
As	1.10E-08	1.10E-08				1.36E-05		
Cd	3.11E-09	3.11E-09				5.03E-06		
Cr	8.44E-09	8.44E-09				1.36E-05		1.97E-05
Cu	7.71E-09	7.71E-09				1.24E-05		
Ni	1.07E-08	1.08E-08				1.73E-05		
Pb	1.86E-08	1.86E-08			2.00E-04	3.00E-05	1.14E-03	
Se						1.98E-05		
Zn						1.60E-04	1.13E-02	

*Sources provided by The Guidebook 2007

Mercury

The following table provides an overview of the different sources to the emission factors for mercury for human cremation. With the exception of EB2009/GB2007 there is good compliance between the different sources. To support consistency, WebFIRE is recommended as the source for a mercury emission factor.

Mercury emission factors, kg/cremated body

	GB2009	US-EPA 1996*	TNO 1992*	NAEI, 2012	OMINEA 2011	Switzerland IIR 2011	Sweden IIR, 2008	WebFIRE	Kriegbaum and Jensen, 2005	Santarsiero et al, 2005b
Hg	9.34E-07	9.34E-07	5.00E-03	2.08E-03	1.43E-03	8.00E-04	3.87E-03	1.49E-03	1.12E-03	5.43E-04

	Netherland IIR 2012	Schleicher and Gram, 2008	Defra 2004	Basu and Wilson, 1988**	US-EPA, 1999 **	NESCAUM, 2005	UK newspaper, 2001**	Norway researcher, 2001**	Norwegian EPA**	Tetra, 2007
Hg	1.73E-03	2.5E-03	1.92E-03	2.10E-03	2.03E-04	2.90E-03	2.95E-03	5.13E-03***	4.90E-03	3.20E-03

*It has not been possible to obtain this source, data is provided by The Guidebook 2007, **It has not been possible to obtain this source, data is provided by Reindl, 2008,
***Calculated from 0.8 mg Hg/Nm^3 and the average of 3500 Nm^3/hr in 2 hrs and 3880 Nm^3/hr in 1.5 hrs.

PAHs, PCDD/F, PCBs, HCB

The following table provides an overview of the different sources to the emission factors for PAHs, PCDD/F, PCBs and HCB for human cremation. It has not been possible to find any sources to verify the emission factors for benzo(b)flouranthene, benzo(k)flouranthene, benzo(g,h,i)perylene and indeno(1,2,3-c,d)pyrene) given by WebFIRE. There is no clear compliance between the different sources of emissions factors for this group of compounds; it is recommended that WebFIRE is used as the source for PAHs and PCDD/F and that Toda (2006) is used as the source for PCBs and HCB.

Table ww PAHs, PCDD/F, PCBs and HCB emission factors, kg/cremated body

	GB2009	US-EPA 1996*	Wang et al., 2003	NAEI, 2012	Finland IIR 2012	Sweitz IIR 2011	Takeda et al., 2000	Hansen and Hansen 2002	Irland IIR 2011	Sweden IIR, 2008	WebFIRE	Hansen, 2000
benzo(b)flouranthen											7.21E-09	
benzo(k)flouranthen											6.44E-09	
benzo(g,h,i)perylen											1.32E-08	
indeno(1,2,3-c-d)pyrene											6.99E-09	
benzo(a)pyrene	1.03E-11	1.03E-11							1.00E-08		1.32E-08	
flouranthene		5.90E-11									9.30E-08	
PAH					6.50E-05						1.40E-07	
PCDD/F	1.68E-11	1.68E-11	1.4E-08	2.47E-08	1.95E-10	4.95E-12	9.95E-12	4.98E-10	2.47E-08	9.00E-09	2.67E-11	2.83E-10
PCBs					2.60E-08							
HCB				5.00E-07								

	Henriksen et al., 2006	Schleicher et al., 2001	Norway IIR 2012	Santarsiero et al, 2005b	Toda, 2006	UNEP Toolkit, 2005	NPI crematoria, 2011	European commission, 2006	Belgium IIR 2010 Flanders	Belgium IIR 2010 Wallonia	Belgium IIR 2010 Brussels
benzo(b)flouranthen											
benzo(k)flouranthen											
benzo(g,h,i)perylen											
indeno(1,2,3-c-d)pyrene											
benzo(a)pyrene											
flouranthene											
PAH			4.90E-04				2.60E-05				
PCDD/F	9.50E-10	3.25E-10	9.99E-09	2.40E-03		1.00E-08	4.9E-09	3.25E-10	5.04E-11	4.00E-09	7.9E-09
PCBs					4.14E-07			2.60E-08			
HCB					1.52E-07						

*Sources provided by The Guidebook 2007

Incineration of carcasses

Comparing the recommended TSP EF for human cremation given by WebFIRE with the tier 2 EFs for open burning of sheep and cows, emissions are 0.59 kg/Mg, 2.18 kg/Mg and 0.897 kg/Mg for human, sheep and cows respectively. It seems reasonable at human cremation causes less particle emission than open burning of animal carcasses. The difference between sheep and cows appears large, but no other data has been found to suggest that the current data are unreasonable.

Small scale waste burning

Small-scale waste burning as in the current GB consists of a tier 1 EF table, and tier 2 EFs for leaf burning, forest residues, orchard crops, weeds, vine crops, backfire burning and headfire burning.

In the current GB chapter there is EFs for NMVOC, NH_3, TSP, PM_{10}, $PM_{2.5}$, PCDD/F and total PAH. However, when reviewing the EFs, the following observations are made: the EFs provided for NMVOC, NH_3, PCDD/F and total PAH are identical for tier 1 and all available tier 2 tables.

The TSP EFs are from a previous version of the GB and are not referenced. The calculation of PM_{10} and $PM_{2.5}$ is based on particle size distribution from crude oil plumes!

Furthermore, the tier 1 TSP EF is lower than all of the tier 2 TSP EF.

It is difficult to defend the current level of disaggregation considering that the only EFs that vary across the different tier 2 EF tables are PM and that these factors are not referenced.

Recommendation

It is proposed to use data by Jenkins et al. (1996) to develop EFs for forest residues (Douglas fir slash & Ponderosa pine slash) and orchard crops (Almond prunings & Walnut prunings). The detailed data by Jenkins et al. will also increase the completeness of the EF tables since it covers more pollutants, e.g. it will be possible to include EFs of heavy metals and the four PAH compounds.

Based on the two tier 2 data sets the tier 1 EFs can be developed as the average value.

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