# International Environmental Agreements and Directed Technological Change: Evidence from the Ozone Regime

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September 4, 2019

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# Contents

# 1 Background on Ozone and the Montreal Protocol

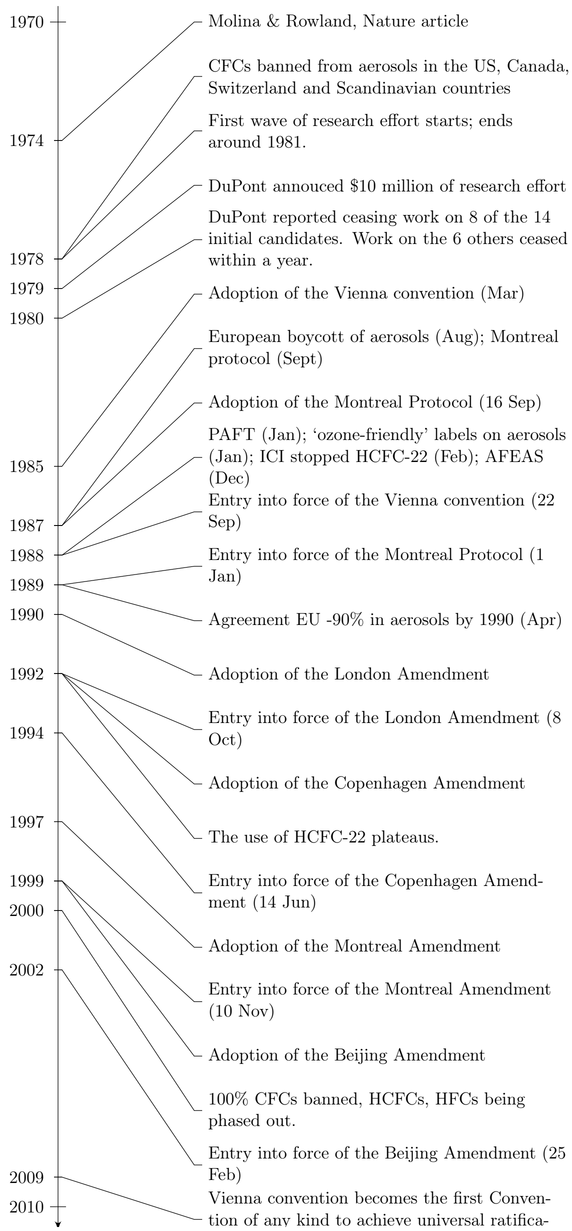


Figure 1: Timeline of events related to CFCs and the Montreal protocol

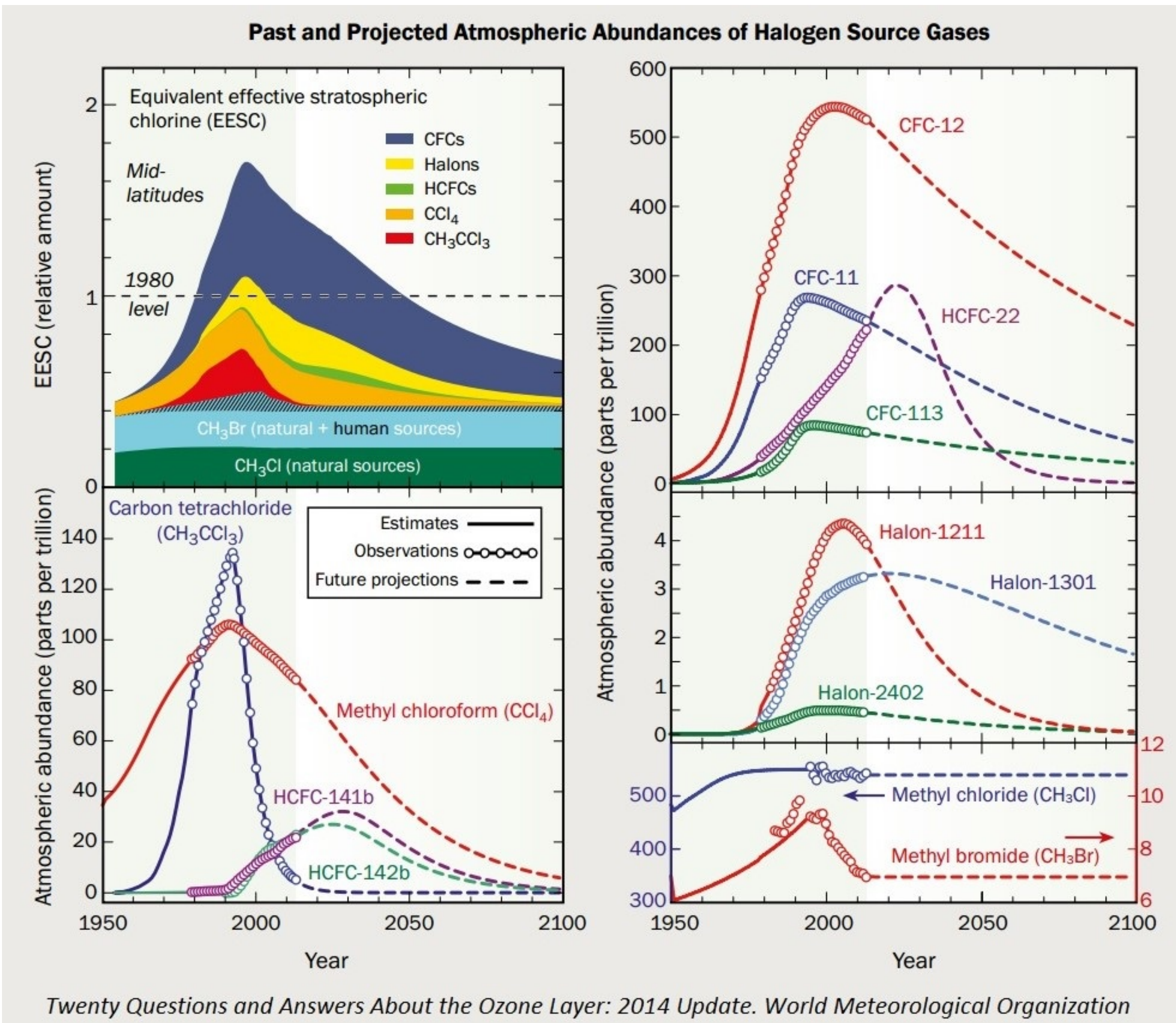


Figure 2: CFC concentrations: past and projected.

Table 1: Details about substitutes to ODS. Information collected from (Parson 2003) and (Benedick 2009). Note: the cost of CFC-12 in 1986 was $0.65/lb.

| Substitute | PAFT | AFEAS | Substitute for | Notes |
|---|---|---|---|---|
| HCFC-22 | No, already marketed, toxicology known | Yes | Included in Annex C. CFC-11, CFC-12 in foams | cheapest, fastest substitute, already at large scale production at the end of 1986 but due to toxicity concerns, not appropriate for aerosol use. FDA approved it for foams in 1988 for fast foods and for grocery display packaging. |
| HCFC-142b | No, already marketed, toxicology known | Yes | CFC-11, CFC-12 but not ideal | Included in Annex C. Considered because already at small scale production in 1986 but their thermodynamic propertiesare very different and would have required changes in equipment and process. DuPont 1988 process for coproduction of HCFC 141b and 142b |
| HFC-152a | No, already marketed, toxicology known | Yes | CFC-11, CFC-12 but not ideal | Considered because already at small scale production in 1986 but their thermodynamic propertiesare very different and would have required changes in equipment and process. |
| HCFC-123 | Yes | Yes | CFC-11 in refrigeration | Included in Annex C. Vapor pressure similar to CFC-11 and CFC-12 implied no need to change equipment. However no commercial experience. estimated at $1.5-2/lb in 1986. DuPont patent commercial synthesis route 1988. large plant in 1990 for production. Still some toxicity concerns. |
| HFC-134a | Yes | Yes | CFC-12 in refrigeration (car AC) | vapor pressure similar to CFC-11 and CFC-12 implied no need to change equipment. However no commercial experience. estimated at $3/lb in 1986. oct 1990 first commercial plant ICI, then DuPont. Both DuPont and ICI announced important catalyst breakthroughs in 1992, which roughly doubled their capacity. |
| HCFC-141b | Yes | Yes | CFC-11 in foams | Included in Annex C. Vapor pressure similar to CFC-11 and CFC-12 implied no need to change equipment. However no commercial experience. DuPont 1988 process for coproduction of HCFC 141b and 142b. Appeared to be the most promising alternative initially (1987-1988) but in late 1988 its ODP was found much higher than thought (about 10 percent). EPA banned its use as a solvent in 1993. required phase out of production by 2003. Moderate inflammability. |
| HCFC-124 | Yes | Yes | CFC-114 in refrigeration and sterilization | Included in Annex C. Less suitable properties but could be used in blends |
| HCFC-125 | Yes | Yes | CFC-115 in refrigeration and sterilization | less suitable properties but could be used in blends |
| HCFC-225ca | No, second rank candidate | Yes | | Included in Annex C. |
| HCFC-225cb | No, second rank candidate | Yes | | Included in Annex C. |
| HFC-32 | No, second rank candidate | Yes | refrigeration | considered in blends for refrigeration. Inflammability and compressor discharge made it problematic alone. Both DuPont and ICI opened HFC-32 plants in the summer of 1992. by 1993, DuPont, Allied, ICI, and Atochem were all marketing various patented refrigerant blends |
| HFC-143a | No, second rank candidate | Yes | CFC-12 in refrigeration | less suitable properties but could be used in blends |
| HFC-245fa | No | No | CFC-11, HCFC-141b and HCFC-142b in foams | |
| HFC-365mfc | No | No | CFC-11, HCFC-141b and HCFC-142b in foams | |

Table 2: Montreal Protocol Phaseout Schedules. Source: Benedick (2009)

| Chemicals | 1987 Montreal Protocol | 1990 London Revisions | 1992 Copenhagen Revisions | 1995 Vienna Revisions | 1995 Vienna (article 5) |
|---|---|---|---|---|---|
| Annex A/I Chlorofluorocarbons 11,12,113,114,115 | baseline 1986 freeze 1989 20% 1993 50% 1998 | baseline 1986 freeze 1989 50% 1995 85% 1997 ... | baseline 1986 freeze 1989 75% 1994 100% 1996 | no change | baseline 1995/97 freeze 1999 50% 2005 85% ... |
| Annex A/II Halons 1211, 1301, 2402 | baseline 1986 freeze 1992 | baseline 1986 freeze 1992 50% 1995 100% 2000 | baseline 1986 freeze 1992 100% 1994 | no change | baseline 1995/97 freeze 2002 50% 2005 100% ... |
| Annex B/I Other CFCs 10 chemicals | no controls | baseline 1989 20% 1993 85% 1997 100% 2000 | baseline 1989 20% 1993 75% 1994 100% 1996 | no change | baseline 1998/2000 20% 2003 85% 2007 100%... |
| Annex B/II Carbon tetrachloride | | baseline 1989 85% 1995 100% 2000 | baseline 1989 85% 1995 100% 1996 | no change | baseline 1998/2000 85% 2005 100% 2010 |
| Annex B/III Methyl chloroform | | baseline 1989 freeze 1993 30% 1995 70% 2000 ... | baseline 1989 freeze 1993 50% 1994 100% 1996 | no change | baseline 1998/2000 freeze 2013 30% 2005 70% ... |
| Annex C/I Hydrochlorofluorocarbons 40 chemicals | no controls | mandatory re-porting nonbiding reso-lution on pase-out: 2020 if pos... | baseline 1989 freeze 1996 35% 2004 65% 2010 90% 201... | baseline 1989 one change | baseline 2015 freeze 2016 100% 2040 |
| Annex C/II Hydrobromofluorocarbons 34 chemicals | no controls | no controls | 100% 1996 | no change | 100% 1996 |
| Annex E Methyl bromide | no controls | no controls | baseline 1991 freeze 1995 | baseline 1991 freeze 1995 25% 2001 50% 2005 100% 2010 | baseline 1995/98 freeze 2002 |

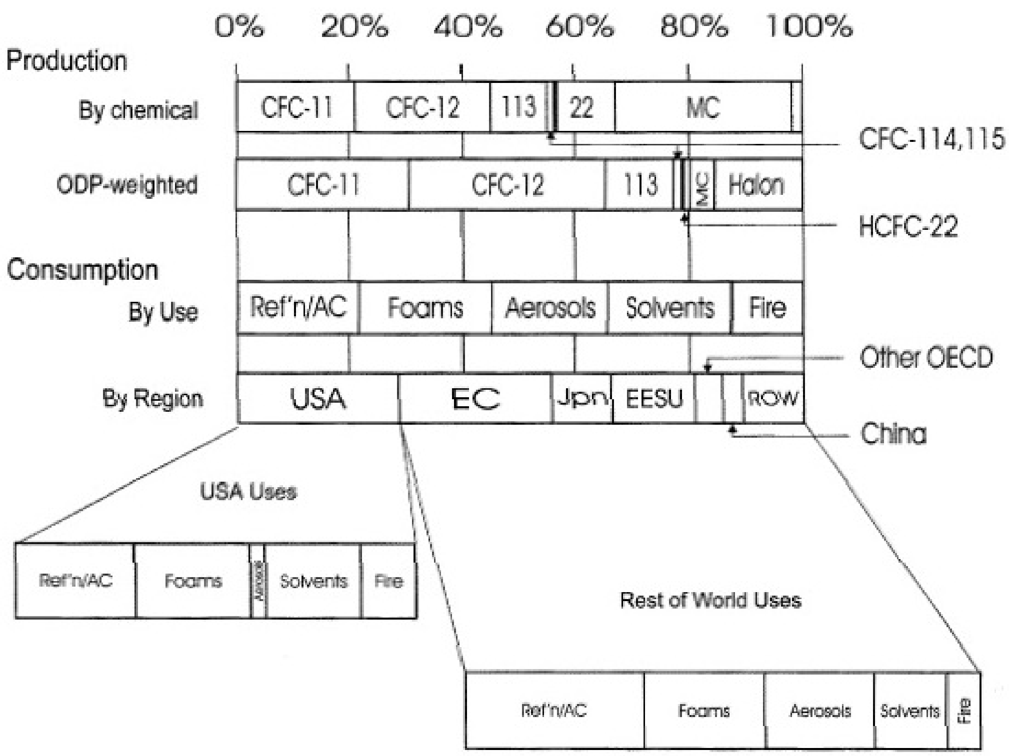


Figure 3: World consumption and production of ozone-depleting chemicals in 1986.
*Source: Parson (2003) page 174. Notes: MC stands for methyl chloroform.*

# 2 Background Information on the Molecules

**HCFC 22**
Chlorodifluoromethane
Algeon 22
Algofrene 22
Algofrene 6
Arcton 22
Arcton 4
CFC 22
Daiflon 22
Difluorochloromethane
Difluoromethyl chloride
Difluoromonochloromethane
Dymel 22
Electro-CF 22
F 22 (halocarbon)
FC 22
FC 22 (halocarbon)
FKW 22
Flugene 22
Forane 22
Freon 22
Freon R 22
Frigen 22
Fron 22
Genetron 22
HFA 22
Halon 22
Haltron 22
Isceon 22
Isotron 22
Khladon 22
Korfron 22
Monochlorodifluoromethane
Propellant 22
R 22
Refrigerant 22
Refrigerant R 22
Solkane 22
Ucon 22

**HCFC 123**
2,2-Dichloro-1,1,1-trifluoroethane
1,1,1-Trifluoro-2,2-dichloroethane
1,1,1-Trifluorodichloroethane
1,1-Dichloro-2,2,2-trifluoroethane
CFC 123
Dichloro(trifluoromethyl)methane
F 123
F 123 (halocarbon)
FC 123
Freon 123
Fron 123
HFA 123
Khladon 123
R 123
Solkane 123

**HCFC 124**
2-Chloro-1,1,1,2-tetrafluoroethane
1,1,1,2-Tetrafluoro-2-chloroethane
1,1,1,2-Tetrafluorochloroethane
1-Chloro-1,2,2,2-tetrafluoroethane
CFC 124
F 124
F 124 (halocarbon)
FC 124
Freon 124
Fron 124
Khladon 124
R 124

**HCFC 125**
Ethane, pentafluoro- (6CI,7CI,8CI,9CI)
1,1,1,2,2-Pentafluoroethane
1,1,2,2,2-Pentafluoroethane
Ecolo Ace 125
F 125
FC 125
Freon 125
Fron 125
HFA 125
HFC 125
HFO 125
Khladon 125
Pentafluoroethane
R 125

**HCFC 141b**
1,1-Dichloro-1-fluoroethane
1-Fluoro-1,1-dichloroethane
141B
Asahiklin AK 141b
CFC 141b
CG 141b
Daiflon 141b
Dichlorofluoroethane
F 141b
Forane 141b
Forane DGX
Fron 141b
Genesolv 2000
Genetron 141b
HFA 141b
HFC 141b
Isotron 141b
Khladon 141b
R 141b
RC 14
Refrigerant 141b
Solkane 141b

**HCFC 142b**
1-Chloro-1,1-difluoroethane
1,1-Difluoro-1-chloroethane
CFC 142b
Daiflon 142b
Dymel 142
F 142b
FC 142b
FKW 142b
Freon 142b
Fron 142b
Genetron 101
Genetron 142b
HFA 142b
Propellant 142B
R 142b
Solkane 142b
Îś-Chloroethylidene fluoride

**HCFC 152a**
1,1-Difluoroethane
Algofrene 67
Dymel 152
Dymel 152A
Ethylidene fluoride
F 152A
FC 152a
FKW 152a
Formacel Z 2
Fron 152a
Genetron 152A
HFA 152a
HFC 152a
HFO 152a
Propellant 152A
R 152a
Solkane 152a TG 152a

**HCFC-225ca**
3,3-Dichloro-1,1,1,2,2-pentafluoropropane
1,1,1,2,2-Pentafluoro-3,3-dichloropropane
1,1-Dichloro-2,2,3,3,3-pentafluoropropane
Fron 225
R 225b
R 225ca

**HCFC-225cb**
1,3-Dichloro-1,1,2,2,3-pentafluoropropane
1,1,2,2,3-Pentafluoro-1,3-dichloropropane
AK 225G
AK 225cb
Asahiklin AK 225G
HFC 225bc
R 225a
R 225cb

**HCFC 134a**
1,1,1,2-Tetrafluoroethane
1,2,2,2-Tetrafluoroethane
AK 134a
Arcton 134a
Ecolo Ace 134a
F 134A
FC 134a
Forane 134a
Freon 134a
Fron 134a
Genetron 134a
HC 134a
HFA 134
HFA 134a
HFA P134a
HFC 134a
Halon 134A
KLEA 134a
Khladon 134a
Meforex 134a
Norflurane
P 134A
R 134a
RF 134a
Refrigerant R 134a
SUVA 134a
Solkane 134a
TG 134a

**HCFC 143a**
1,1,1-Trifluoroethane
CFC 143A
F 143A
FC 143a
Freon 143a
Fron 143a
HCF 143a
HFA 143a
HFC 143a
HFO 143a
Methylfluoroform
R 143a
TG 143a

**HFC 245fa**
1,1,1,3,3-Pentafluoropropane
1,1,3,3,3-Pentafluoropropane
245fa
Enovate 245
Enovate 245fa
Enovate 3000
Genetron 245fa

**HFC 32**
Difluoromethane
Ecolo Ace 32
F 32
FC 32
Forane 32
Freon 32
Genetron 32
HFA 32
HFO 32
Methylene difluoride
R 32
R 32 (refrigerant)

**HFC 365mfc**
1,1,1,3,3-Pentafluorobutane
2,2,4,4,4-Pentafluorobutane

Forane 365mfc
HFC 365
HFO 365mfc
R 365
R 365mfc
Solkane 365
Solkane 365mfc

Figure 4: List of substitutes and their possible names

# References

Benedick, Richard Elliot (2009). *Ozone Diplomacy: New Directions in Safeguarding the Planet.* Harvard University Press.

Parson, Edward A (2003). *Protecting the Ozone Layer: Science and Strategy*. Oxford University Press.

| | |
|---|---|
| CFC Substitutes | HCFC 22, HCFC 123, HCFC 124, HCFC 125, HCFC 141b, HCFC 142b, HCFC 225ca, HCFC 225cb, HFC 134a, HFC 143a, HFC 152a, HFC 245fa, HFC 32, HFC 365mfc |
| Annex A | CFC 11, CFC 12, CFC 113, CFC 114, CFC 115, HALON 1211, HALON 1301, HALON 2402 |
| Annex B | CFC 13, CFC 111, CFC 112, CFC 211, CFC 212, CFC 213, CFC 214, CFC 215, CFC 216, CFC 217, Carbon tetrachloride, Methyl chloroform |
| HAPs | Acetaldehyde, Acetamide, Acetonitrile, Acetophenone, 2-Acetylaminofluorene, Acrolein, Acrylamide, Acrylic acid, Acrylonitrile, Allyl chloride, 4-Aminobiphenyl, Aniline, o-Anisidine, Asbestos, Benzene, Benzidine, Benzotrichloride, Benzyl chloride, Biphenyl, Bis(2-ethylhexyl)phthalate (DEHP), Bis(chloromethyl)ether, Bromoform, 1,3-Butadiene, Calcium cyanamide, Caprolactam, Captan, Carbaryl, Carbon disulfide, Carbonyl sulfide, Catechol, Chloramben, Chlordane, Chlorine, Chloroacetic acid, 2-Chloroacetophenone, Chlorobenzene, Chlorobenzilate, Chloroform, Chloromethyl methyl ether, Chloroprene, Cresols/Cresylic acid, o-Cresol, m-Cresol, p-Cresol, Cumene, 2,4-D, salts and esters, DDE, Diazomethane, Dibenzofurans, 1,2-Dibromo-3-chloropropane, Dibutylphthalate, 1,4-Dichlorobenzene, 3,3-Dichlorobenzidene, Dichloroethyl ether ether), 1,3-Dichloropropene, Dichlorvos, Diethanolamine, N,N-Dimethylaniline, Diethyl sulfate, 3,3-Dimethoxybenzidine, Dimethyl aminoazobenzene, 3,3'-Dimethyl benzidine, Dimethyl carbamoyl chloride, Dimethyl formamide, 1,1-Dimethyl hydrazine, Dimethyl phthalate, Dimethyl sulfate, 4,6-Dinitro-o-cresol, and salts, 2,4-Dinitrophenol, 2,4-Dinitrotoluene, 1,4-Dioxane, 1,2-Diphenylhydrazine, Epichlorohydrin, 1,2-Epoxybutane, Ethyl acrylate, Ethyl benzene, Ethyl carbamate, Ethyl chloride, Ethylene dibromide, Ethylene dichloride, Ethylene glycol, Ethylene imine, Ethylene oxide, Ethylene thiourea, Ethylidene dichloride, Formaldehyde, Heptachlor, Hexachlorobenzene, Hexachlorobutadiene, Hexachlorocyclopentadiene, Hexachloroethane, Hexamethylene-1,6-diisocyanate, Hexamethylphosphoramide, Hexane, Hydrazine, Hydrochloric acid, Hydrogen fluoride, Hydrogen sulfide, Hydroquinone, Isophorone, Lindane, Maleic anhydride, Methanol, Methoxychlor, Methyl bromide, Methyl chloride, Methyl ethyl ketone, Methyl hydrazine, Methyl iodide, Methyl isobutyl ketone, Methyl isocyanate, Methyl methacrylate, Methyl tert butyl ether, 4,4-Methylene bis(2-chloroaniline), Methylene chloride, Methylene diphenyl diisocyanate, 4,4'-Methylenedianiline, Naphthalene, Nitrobenzene, 4-Nitrobiphenyl, 4-Nitrophenol, 2-Nitropropane, N-Nitroso-N-methylurea, N-Nitrosodimethylamine, N-Nitrosomorpholine, Parathion, Pentachloronitrobenzene, Pentachlorophenol, Phenol, p-Phenylenediamine, Phosgene, Phosphine, Phosphorus, Phthalic anhydride, Polychlorinated biphenyls, 1,3-Propane sultone, beta-Propiolactone, Propionaldehyde, Propoxur, Propylene dichloride, Propylene oxide, 1,2-Propylenimine, Quinoline, Quinone, Styrene, Styrene oxide, 2,3,7,8-Tetrachlorodibenzo-p-dioxin, 1,1,2,2-Tetrachloroethane, Tetrachloroethylene, Titanium tetrachloride, Toluene, 2,4-Toluene diamine, 2,4-Toluene diisocyanate, o-Toluidine, Toxaphene, 1,2,4-Trichlorobenzene, 1,1,2-Trichloroethane, Trichloroethylene, 2,4,5-Trichlorophenol, 2,4,6-Trichlorophenol, Triethylamine, Trifluralin, 2,2,4-Trimethylpentane, Vinyl acetate, Vinyl bromide, Vinyl chloride, Vinylidene chloride, Xylenes, o-Xylenes, m-Xylenes, p-Xylenes |

Table 3: List molecules in each treatment group