

Annex B

Methodology for Estimating Carbon Stored in Products from Non-Energy Uses of Fossil Fuels

Carbon storage associated with the non-energy use of fossil fuels was calculated by multiplying each fuel's potential emissions (i.e., each fuel's total carbon content) by a fuel-specific storage factor. This Annex explains the methods and data sources employed in revising the storage factors for asphalt and road oil, petrochemical feedstocks, liquid petroleum gases (LPG), pentanes plus, and natural gas for chemical plants. The storage factors for the remaining non-energy fuel uses are based on values reported by Marland and Rotty (1984).

Table B-1: Fuel Types and their Non-Energy Storage Factors

Fuel Type	Storage Factor
Industrial Coking Coal	0.75
Natural Gas to Chemical Plants	-
Nitrogenous Fertilizers	0
Other Uses	0.91
Asphalt & Road Oil	1.00
Liquefied Petroleum Gas (LPG)	0.91
Lubricants	0.09
Pentanes Plus	0.91
Petrochemical Feedstocks ^a	-
Naphtha (b.p. < 401° F)	0.91
Other Oil (b.p. > 401° F)	0.91
Petroleum Coke	0.50
Special Naphtha	0
Other	-
Distillate Fuel Oil	0.50
Residual Fuel	0.50
Waxes	1.00
Miscellaneous Products ^b	1.00

- Not applicable

^a Includes still gas, for which EIA has reported zero consumption in 1996, 1998, and 1999.

^b Because of differences in fuel characteristics between the United States and U.S. Territories, the storage factor for Miscellaneous Products consumed in U.S. Territories is set at 0.1.

The following sections describe the selected non-energy uses in greater detail, outlining the methods employed and data used in estimating each storage factor. Several of the fuel types tracked by EIA—petrochemical feedstocks, pentanes plus, LPG, and natural gas—are used in organic chemical synthesis. Because the methods and data used to analyze these fuel types overlap, they are handled as a group and are discussed first. Discussions of the storage factors for (a) asphalt and road oil, and (b) lubricants follow.

Petrochemical Feedstocks, Pentanes Plus, Liquefied Petroleum Gases, and Natural Gas

Petrochemical feedstocks, pentanes plus, liquefied petroleum gases (LPG) and natural gas¹ are used in the manufacture of a wide variety of man-made chemicals and products. Plastics, rubber, synthetic fibers, solvents, paints, fertilizers, pharmaceuticals, and food additives are just a few of the derivatives of these four fuel types.

¹ Natural gas has two categories of non-energy consumption: for fertilizer and for other chemical syntheses. Only natural gas that is supplied to chemical plants for other uses is included here. Natural gas used for fertilizer is not included because it is assumed that all of the carbon is converted to carbon dioxide during ammonia synthesis.

Chemically speaking, these fuels are diverse, ranging from simple natural gas (i.e., predominantly methane, CH₄) to heavier, more complicated naphthas and fuel oils.²

The four fuel categories constituted approximately 247 Tg CO₂ Eq., or 52 percent, of the 478 Tg CO₂ Eq. of non-energy fuel consumption in 1999. Of this, 223 Tg CO₂ Eq., or 91 percent, of the carbon ends up stored in products, while the remaining 23 Tg CO₂ Eq. was emitted as an industrial process waste or through evaporative product use. These emissions can be thought of as a variety of organic gases; however, most of these emissions will eventually oxidize into carbon dioxide in the atmosphere.

Methodology and Data Sources

An empirically determined storage factor was developed for the carbon consumed for non-energy end uses among petrochemical feedstocks, pentanes plus, LPG, and natural gas. The storage factor is equal to the ratio of carbon stored in the final products to total carbon content for the nonenergy fossil fuel feedstocks diverted to industrial processes. Only one aggregate storage factor was calculated for the four fuel types. As noted above, the fuels were grouped because of the overlap of their derivative products. Due to the many reaction pathways involved in producing petrochemical products (or wastes), it becomes extraordinarily complex to link individual products (or wastes) to their parent fuels.

The overall storage factor was determined by investigating the carbon used in manufacturing the major petrochemical products. Plastics, synthetic rubber, synthetic fibers, carbon black, industrial volatile organic compound (VOC) emissions, industrial toxic releases, pesticides, and solvents were identified as the major product categories.³ Estimating the carbon stored by the non-energy use of petrochemical feedstocks, pentanes plus, LPG, and natural gas requires two pieces of information for each of the major products that are derived from these fuels. First, the total amount of carbon contained in the product or waste must be determined. The total carbon content of the fuels was calculated by multiplying the fuels' non-energy consumption by their respective carbon content values. Similar to fuel consumed for energy purposes, the consumption data was taken from EIA (2000). Carbon content values are discussed in Annex A.

Next, the carbon must be categorized as either stored or emitted. The aggregate storage factor is the carbon-weighted average of storage across the fuel types. As discussed later in the section on Uncertainty, data were not available for all of the non-energy end uses, so the uses analyzed represent only a sample of the total carbon consumed. The sample accounts for 151 Tg CO₂ Eq., or 62 percent, of the 247 Tg CO₂ Eq. of carbon within these fuel types that is consumed for non-energy purposes. The remaining carbon is assumed to be stored and emitted in the same ratio as the products for which data are available. The following sections provide details on the calculation steps, assumptions, and data sources employed in estimating and classifying each product's carbon. Summing the carbon stored and dividing it by the total carbon used yields the overall storage factor, as shown in Table B-2 and the equation below. The major products and their carbon contents are also shown in Table B-2.

$$\text{Overall Storage Factor} = \text{Carbon Stored} / \text{Total Carbon} = 136.3 \text{ Tg CO}_2 \text{ Eq.} / 150.5 \text{ Tg CO}_2 \text{ Eq.} = 91\%$$

² Naphthas are compounds distilled from petroleum containing 4 to 12 carbon atoms per molecule and having a boiling point less than 401° F. Fuel oils are distillates containing 12 to 25 carbon atoms per molecule and having a boiling point greater than 401° F.

³ For the most part, the releases covered by the U.S. Toxic Release Inventory represent air emissions or water discharges associated with production facilities. Similarly, VOC emissions are generally associated with production facilities. These emissions could have been accounted for as part of the Waste chapter, but because they are not necessarily associated with waste management, they were included here instead. Toxic releases are not a "product" category, but they are referred to as such for ease of discussion.

Table B-2: Carbon Stored and Emitted by Products from Petrochemical Feedstocks, Pentanes Plus, LPG, and Natural Gas (Tg CO₂ Eq.)

Product/Waste Type	Carbon Stored	Carbon Emitted
Plastics	110.4	-
Synthetic Rubber	7.7	-
Synthetic Fiber	11.7	-
Carbon Black	5.9	-
Pesticides	0.4	0.2
Industrial Releases	0.10	4.8
Industrial VOCs	-	3.8
TRI Releases	0.1	1.0
Solvent VOCs	-	9.3
Total	136.3	14.3

- Not applicable

Plastics

Data on annual production were taken from the American Plastics Council, as published in *Chemical & Engineering News* and through direct communication with the APC (APC 2000, Eldredge-Roebuck 2000). These data were organized by year and resin type (Table B-3). A carbon content was assigned for each resin. These contents were based on molecular formulas and are listed in Table B-4 and Table B-5. In cases where the resin type is generic, referring to a group of chemicals and not a single polymer (e.g., phenolic resins, other styrenic resins), a representative compound was chosen. For engineering and other resins, a weighted carbon content of 65 percent was assumed (i.e., it was assumed that these resins had the same content as those for which we could assign a representative compound).

There were no emissive uses of plastics identified, so 100 percent of the carbon was considered stored in products. However, an estimate of emissions related to the combustion of these plastics in the municipal solid waste stream can be found in the Waste Combustion section of the Waste chapter.

Table B-3: 1998 Plastic Resin Production (Tg dry weight) and Carbon Stored (Tg CO₂ Eq.)

Resin Type	1998 Production ^a	Carbon Stored
Epoxy	0.29	0.8
Polyester (Unsaturated)	0.78	1.8
Urea	1.17	1.5
Melamine	0.13	0.1
Phenolic	1.79	5.0
Low-Density Polyethylene (LDPE)	3.44	10.8
Linear Low-Density Polyethylene (LLDPE)	3.28	10.3
High Density Polyethylene (HDPE)	5.86	18.4
Polypropylene (PP)	6.27	19.7
Acrylonitrile-butadiene-styrene (ABS)	0.65	2.0
Styrene-acrylonitrile (SAN)	0.06	0.2
Other Styrenics	0.75	2.5
Polystyrene (PS)	2.83	9.6
Nylon	0.58	1.4
Polyvinyl chloride (PVC) ^b	6.58	9.3
Thermoplastic Polyester	2.01	4.6
Engineering Resins	1.25	3.0
All Other	3.88	9.4
Total	41.59	110.4

^a Includes production from Canada for ABS, SAN, PVC, PP, Phenolic, Urea, Melamine, and Thermoplastic Polyester.

^b Includes copolymers.

Table B-4: Assigned Carbon Contents of Plastic Resins (by weight)

Resin Type	Carbon Content	Source of Carbon Content Assumption
Epoxy	76%	Typical epoxy resin made from epichlorhydrin and bisphenol A
Polyester (Unsaturated)	63%	Poly (ethylene terephthalate) (PET)
Urea	34%	50% carbamal, 50% N-(hydroxymethyl) urea *
Melamine	29%	Trimethylol melamine *
Phenolic	77%	Phenol
Low-Density Polyethylene (LDPE)	86%	Polyethylene
Linear Low-Density Polyethylene (LLDPE)	86%	Polyethylene
High Density Polyethylene (HDPE)	86%	Polyethylene
Polypropylene (PP)	86%	Polypropylene
Acrylonitrile-Butadiene-Styrene (ABS)	85%	50% styrene, 25% acrylonitrile, 25% butadiene
Styrene-Acrylonitrile (SAN)	80%	50% styrene, 50% acrylonitrile
Other Styrenics	92%	Polystyrene
Polystyrene (PS)	92%	Polystyrene
Nylon	65%	Average of nylon resins (see Table B-5)
Polyvinyl Chloride (PVC)	38%	Polyvinyl chloride
Thermoplastic Polyester	63%	Polyethylene terephthalate
Engineering Resins	66%	Weighted average of other resin production
All Other	66%	Weighted average of other resin production

*Does not include alcoholic hydrogens.

Table B-5: Major Nylon Resins and their Carbon Contents (by weight)

Nylon Resin	Carbon Content
nylon 6	64%
nylon 6,6	64%
nylon 4	52%
nylon 6,10	68%
nylon 6,11	69%
nylon 6,12	70%
nylon 11	72%

Synthetic Rubber

Annual consumption of synthetic rubber was taken from the International Institute of Synthetic Rubber Producers (IISRP) press release “Synthetic Rubber Use Growth to Continue Through 2004, Says IISRP and RMA” (IISRP 2000). Due to the fact that production data for synthetic rubber were unavailable, consumption was assumed to equal production and used in the calculations. This data is organized by year, and by elastomer type. For each resin, a carbon content was assigned. These contents, based on stoichiometry, are listed in Table B-6. For the “Others” category, a weighted carbon content was calculated from total 1998 resin consumption data.

There were no emissive uses of rubber identified, so 100 percent of the carbon was assumed stored. However, emissions related to the combustion of scrap tires and rubber consumer goods can be found in the Waste Combustion section of the Waste chapter.

Table B-6: 1998 Rubber Consumption, Carbon Content, and Carbon Stored

Elastomer Type	1998 Consumption (Thousand Metric Tons) *	Carbon Content	Carbon Stored (Tg CO ₂ Eq.)
SBR Solid	908	91%	3.0
Polybutadiene	561	89%	1.8
Ethylene Propylene	320	86%	1.0
Polychloroprene	69	59%	0.1
NBR Solid	87	77%	0.2
Polyisoprene	78	88%	0.3
Others	369	88%	1.2
Total	2,392	-	7.7

* Includes consumption in Canada.

- Not applicable

Synthetic Fibers

Annual fiber production data was taken from the Fiber Economics Bureau, as published in *Chemical & Engineering News* and exhibited on the FiberSource website (FEB 2000). These data were organized by year and fiber type. For each fiber, a carbon content was assigned based on stoichiometry (see Table B-7). For polyester, the carbon content for poly(ethylene terephthalate) (PET) was used as a representative compound. For nylon, the average carbon content of nylon 6 and nylon 6,6 was used, since these are the most widely produced nylon fibers. Cellulosic fibers, such as acetate and rayon, have been omitted from the synthetic fibers' carbon accounting because much of their carbon is of biogenic origin. These fibers account for only 4 percent of overall fiber production, by weight.

There were no emissive uses of fibers identified, so 100 percent of the carbon was considered stored. However, emissions related to the combustion of textiles in the municipal solid waste stream is accounted for under the Waste Combustion section of the Waste chapter.

Table B-7: 1998 Fiber Production, Carbon Content, and Carbon Stored

Fiber Type	Production (Tg)	Carbon Content	Carbon Stored (Tg CO ₂ Eq.)
Polyester	1.8	63%	4.1
Nylon	1.3	64%	3.0
Olefin	1.3	86%	4.1
Acrylic	0.2	68%	0.5
Total	4.6	-	11.7

- Not applicable

Carbon Black

Carbon black is a finely divided solid form of carbon produced from the partial oxidation of heavy oil fractions.⁴ It is used primarily in tire treads and other abrasion resistant rubber products, but can also be used in pigments for paints and inks. In 1998, carbon black ranked the 35th in chemical production in the United States with 1,610,280 metric tons produced (CMA 1999).

Since carbon black is essentially pure carbon, its carbon content was assumed to be 100 percent. Also, since it is used in solid products and resists degradation, it was considered 100 percent stored. For 1998, carbon stored as a result of carbon black production was estimated to be 5.9 Tg CO₂ Eq. (5,904 Gg).

⁴ Carbon black can also be produced from the cracking of natural gas, but this method is uncommon.

Pesticides

Pesticide consumption data was taken from the *1996/1997 Pesticides Industry Sales and Usage* (EPA 1999) report. Although some production data was available, consumption data was used instead because it provided information on composition, including active ingredients. Active ingredient compound names and consumption weights were available for the top 25 agriculturally-used pesticides and top 9 pesticides used in the Home and Garden and the Industry/Commercial/Government categories. Since the report provides a range of consumption for each active ingredient, the midpoint was used to represent actual consumption. Each of these compounds was assigned a carbon content value based on stoichiometry. If the compound contained an aromatic ring(s) substituted with chlorine or other halogens, then the compound was considered persistent and assigned a 100 percent carbon storage factor. All other pesticides were assumed to release their carbon to the atmosphere. Nearly one-third of total pesticide active ingredient consumption was not specified by chemical type in the *Sales and Usage* report (EPA 1999). This unspecified portion of the active ingredient consumption was treated as a single chemical and assigned a carbon content and a storage factor based on the weighted average of the known chemicals' values.

Table B-8: Active Ingredient Consumption in Pesticides (Million lbs.), and Carbon Emitted and Stored (Tg CO₂ Eq.)

Pesticide Use	Active Ingredient	Carbon Emitted	Carbon Stored
Agricultural Uses ^a	551.0	0.1	0.2
Non-Agricultural Uses ^b	84.5	+	+
Home & Garden	34.0	+	+
Industry/Gov't/Commercial	50.5	+	+
Other	334.5	0.1	0.1
Total	970.0	0.2	0.4

+ Less than 0.05 Tg CO₂ Eq.

^a 1997 estimate (EPA 1999).

^b Approximate quantities, 1995/1996 estimates (EPA 1999).

Industrial and Solvent Volatile Organic Compound Emissions

Data on annual volatile organic compound (VOC) emissions were taken from the *National Air Quality and Emissions Trends Report* (EPA 2000a). Volatile organic compound emissions are organized by end use category. The categories selected to represent "Industrial VOC Emissions" were Chemical and Allied Products, Petroleum and Related Industries, and Other Industrial Processes. Only industrial process categories where the four fuel types would be consumed in a non-energy end-use were included to avoid double-counting. All the VOC emissions from solvent utilization were considered a result of petrochemical non-energy use.

Because emissions are provided in short tons of VOCs, assumptions had to be made concerning the average carbon content of the emissions. The assumptions for calculating the carbon fraction of industrial and solvent utilization emissions were made separately and differ slightly. For industrial VOC emissions, the carbon content was set at 85 percent. This value was chosen to reflect the average carbon content of an average volatile hydrocarbon based on the list of the most abundant, measured VOCs provided in the *Trends Report*. The list contains only pure hydrocarbons, including saturated alkanes (carbon contents ranging from 80 to 85 percent based upon carbon number), alkenes (carbon contents equal 85.7 percent), and some aromatics (carbon contents approximately 90 percent, depending upon substitution).

Due to the hundreds of possible formulations for solvents, the assumptions for the carbon content of the solvent VOCs carry a higher degree of uncertainty. Solvents were split in two categories; half of the solvents were considered to be similar to an aromatic hydrocarbon, and the remainder was considered to be a halogenated, unbranched hydrocarbon. Toluene (carbon content of 91 percent) was selected as the representative aromatic compound; methylene chloride (carbon content of 14 percent) was selected to represent the halogenated compounds. Use of these assumptions yielded an average carbon content of 53 percent.

The results of the industrial and solvent VOC emissions analysis are provided in Table B-9.

Table B-9: 1998 Industrial and Solvent VOC Emissions

Activity	VOC Emissions (Thousand Short Tons)	Carbon Content	Carbon Emitted (Tg CO ₂ Eq.)
Industrial *	1,342	85%	3.8
Solvent Utilization	5,278	53%	9.3

Includes VOC emissions from Chemical and Allied Products, Petroleum and Related Industries, and Other Industrial Processes categories.

TRI Releases

Carbon is also found in toxic substances released by industrial facilities. The Toxic Release Inventory (TRI), maintained by the EPA, tracks these releases by chemical and environmental release medium (i.e., land, air, or water) on a biennial basis (EPA 2000b). By examining the carbon contents and receiving media for the top 35 chemicals released, which account for 90 percent of the total mass of chemicals, the quantity of carbon stored and emitted in the form of toxic releases can be estimated.

The TRI specifies releases by chemical, so carbon contents were assigned based on stoichiometry. The TRI also classifies releases by disposal location as either off-site or on-site. The on-site releases are further subdivided into air emissions, surface water discharges, underground injection, and releases to land; the latter is further broken down to disposal in a RCRA Subtitle C (i.e., hazardous waste) landfill or to "Other On-Site Land Disposal".⁵ The carbon released in each disposal location is provided in Table B-10.

Each on-site classification was assigned a storage factor. One-hundred percent storage was attributed to Underground Injection and disposal to RCRA Landfills, while the other categories were assumed to result in an ultimate fate of emission as CO₂. The release allocation is not reported for off-site releases; therefore, the approach was to develop a carbon-weighted average storage factor for the on-site carbon and apply it to the off-site releases.

For the remaining 10 percent of the TRI releases, the weights of all chemicals were added and an average carbon content value, based upon the top 35 chemicals' carbon contents, was applied. The storage and emission allocation for the remaining 10 percent of the TRI releases was carried out in the same fashion as for the 35 major chemicals.

Table B-10: 1998 TRI Releases by Disposal Location (Gg CO₂ Eq.)

Disposal Location	Carbon Stored	Carbon Emitted
Air Emissions	-	924.0
Surface Water Discharges	-	6.7
Underground Injection	89.4	-
RCRA Subtitle C Landfill Disposal	1.4	-
Other On-Site Land Releases	-	15.9
Off-site Releases	6.4	36.0
Total	97.2	982.6

- Not applicable

Uncertainty

The aggregate storage factor for petrochemical feedstocks, pentanes plus, liquefied petroleum gases, and natural gas is based on only a partial sampling of the products derived from these fossil fuel feedstocks. The products examined only account for 151 Tg CO₂ Eq. (62 percent) of the 247 Tg CO₂ Eq. consumed across these four fuel types for non-energy uses. The remaining 96 Tg CO₂ Eq. of "unaccounted-for" carbon could have a variety of end uses, including chemical intermediates, additives (e.g., plasticizers, vulcanizing agents, food and cosmetic additives), and paints and coatings. These uses have not been explored due to limited data availability. In the absence of better information, the assumption was made that the products which contained the unaccounted for

⁵ Only the top 9 chemicals had their land releases separated into RCRA Landfills and Other Land Disposal. For the remaining chemicals, it was assumed that the ratio of disposal in these two categories was equal to the carbon-weighted average of the land disposal fate of the top 9 chemicals (i.e., 8 percent attributed to RCRA Landfills and 92 percent in the "Other" category).

carbon would store and emit carbon in the same ratio as the investigated products. In the case that the remaining carbon was all stored, the aggregate storage factor (91 percent) would only change slightly to 94 percent. However, if the other end uses were highly emissive (similar to the solvents), then the aggregate storage factor could fall as low as 60 percent.

To a lesser extent, there are uncertainties associated with the simplifying assumptions made for each end use category carbon estimate. Generally, the estimate for a product is subject to one or both of the following uncertainties:

- The value used for estimating the carbon content has been assumed or assigned based upon a representative compound.
- The split between carbon storage and emission has been assumed based on an examination of the environmental fate of the products in each end use category.

These sources of uncertainty are discussed for each product below.

Plastics

Uncertainty in the carbon storage estimate for plastics arises from three sources. First, the production data for acrylonitrile-butadiene-styrene, styrene-acrylonitrile, polyvinyl chloride, polypropylene, phenolic, urea, melamine, and thermoplastic polyester resins include Canadian production and may overestimate the plastic produced from U.S. fuels. Second, the assumed carbon content values are estimates for representative compounds, and thus do not account for the many formulations of resins available. This uncertainty is greater for resin categories that are generic (e.g., phenolics, other styrenics, nylon) than for resins, which have more specific formulations (e.g., polypropylene, polyethylene). Lastly, the assumption that all of the carbon contained in plastics is stored ignores certain end uses (e.g., adhesives and coatings) where the resin may be released to the atmosphere; however, these end uses are likely to be small relative to use in plastics.

Rubber

Similar to plastics, uncertainty results from using consumption data for the United States and Canada, rather than just domestic consumption. There are also uncertainties as to the assignment of carbon content values; however, they are much smaller than in the case of plastics. There are probably fewer variations in rubber formulations than in plastics, and the range of potential carbon content values is much narrower. Lastly, assuming that all of the carbon contained in rubber is stored ignores the possibility of volatilization or degradation during product lifetimes. However, the proportion of the total carbon that is released to the atmosphere during use is probably small.

Fiber

A small degree of uncertainty arises from the assignment of carbon content values; however, the magnitude of this uncertainty is less than that for plastics or rubber. Although there is considerable variation in final textile products, the stock fiber formulations are standardized and proscribed explicitly by the Federal Trade Commission.

Pesticides

The largest source of uncertainty involves the assumption that a pesticide's active ingredient carbon is either 0 or 100 percent stored. This split is a generalization of chemical behavior, based upon active-ingredient molecular structure, not compound-specific environmental data. The mechanism by which a compound is bound or released from soils is very complicated and can be affected by many variables, including the type of crop, the temperature, the delivery method, and the harvesting practice. Another smaller source of uncertainty arises from the carbon content values applied to the unaccounted for portion of active ingredient. Carbon contents vary widely among pesticides, from 7 to 72 percent, and the remaining pesticides may have a chemical make-up that is very different from the 32 pesticides that have been examined.

VOCs

Aside from the dichotomous split applied to solvent VOC emissions, the overall VOC emission estimates incur uncertainty from the assumption that consumption is equivalent to emissions. Some amount of carbon storage may actually be occurring.

TRI

The major uncertainty lies in the storage and emission assumptions. The approach for predicting environmental fate simplifies some complex processes, and the balance between storage and emissions is very sensitive to the assumptions on fate. Extrapolating from known to unknown characteristics also introduces uncertainty. The two extrapolations with the greatest uncertainty are: 1) that the release media and fate of the off-site releases were assumed to be the same as for on-site releases, and 2) that the carbon content of the least frequent 10 percent of TRI releases was assumed to be the same as for the chemicals comprising 90 percent of the releases.

However, the contribution of these chemicals to the overall estimate is small. The off-site releases only account for 3 percent of the total releases, by weight, and, by definition, the less frequent compounds only account for 10 percent of the total releases.

Asphalt

Asphalt is one of the principal non-energy uses of fossil fuels. The term “asphalt” generally refers to a mixture of asphalt cement and a rock material aggregate, a volatile petroleum distillate, or water. For the purposes of this analysis, “asphalt” is used interchangeably with asphalt cement, a residue of crude oil. According to EIA (2000), approximately 100 Tg CO₂ Eq. has been used in the production of asphalt cement annually. Though minor amounts of carbon are emitted during production, asphalt has an overall carbon storage factor of almost 100 percent.

Paving is the primary application of asphalt cement, comprising 86 percent of production. The three types of asphalt paving produced in the United States are hot mix asphalt (HMA), cut-backs, and emulsified asphalt. HMA, which makes up 90 percent of total asphalt paving (EPA 2000c), contains asphalt cement mixed with an aggregate of rock materials. Cut-back asphalt is composed of asphalt cement thinned with a volatile petroleum distillate (e.g., naphtha). Emulsified asphalt contains only asphalt cement and water. Roofing products are the other significant end use of asphalt cement, accounting for approximately 14 percent of U.S. production (Kelly 2000). No data were available on the fate of carbon in asphalt roofing; it was assumed that it has the same fate as carbon in asphalt paving applications.

Methodology

A carbon storage factor was calculated for each type of asphalt paving. The fraction of carbon emitted by each asphalt type was multiplied by consumption data for asphalt paving (EPA 2000c, EIIP 1998) to come up with a weighted average carbon storage factor for asphalt as a whole.

The fraction of carbon emitted by HMA was determined by first calculating the organic emissions (volatile organic compounds [VOCs], carbon monoxide, polycyclic aromatic hydrocarbons [PAHs], hazardous air pollutants [HAPs], and phenol) from HMA paving, using emission factors reported by the EPA (EPA 2000c) and total HMA production.⁶ The next step was to estimate the carbon content of the organic emissions. This calculation was based on stoichiometry for carbon monoxide (CO) and phenol, and an assumption of 85 percent carbon content for PAHs and HAPs. The carbon content of asphalt paving is a function of the proportion of asphalt cement in asphalt paving, and the proportion of carbon in asphalt cement. For the former factor, a 5 percent asphalt cement content was assumed based on personal communication with an expert from the National Asphalt Paving Association (Connolly 2000). For the latter factor, all paving types were characterized as having a mass fraction of 85 percent carbon in asphalt cement, based on the assumption that asphalt is primarily composed of saturated paraffinic hydrocarbons. By combining these estimates, the result is that over 99.99 percent of the carbon in asphalt cement was retained (i.e., stored), and less than 0.01 percent was emitted.

⁶ The emission factors are expressed as a function of asphalt paving tonnage (i.e., including the rock aggregate as well as the asphalt cement).

Cut-back asphalt is produced in three forms (i.e., rapid, medium and slow cure). All three forms emit carbon only from the volatile petroleum distillate used to thin the asphalt cement (EPA 1995). Because the petroleum distillates are not included in the EIA statistics for asphalt, the storage factor for cut-back is assumed to be 100 percent.

It was also assumed that there was no loss of carbon from emulsified asphalt (i.e., the storage factor is 100 percent) based on personal communication with an expert from Akzo Nobel Coatings, Inc. (James 2000).

Data Sources

Data on asphalt and road oil consumption and carbon content factors were supplied by the Energy Information Administration (EIA) of the U.S. Department of Energy (DOE). Hot mix asphalt production and emissions factors were obtained from “Hot Mix Asphalt Plants Emissions Assessment Report” from the EPA publication *AP-42* (EPA 2000c). The asphalt cement content of HMA was provided by Una Connolly of National Asphalt Paving Association (Connolly 2000). The consumption data for cut-back and emulsified asphalts were taken from a Moulthrop, et al. study used as guidance for estimating air pollutant emissions from paving processes (EIIP 1998). “Asphalt Paving Operation” *AP-42* (EPA 1995) provided the emissions source information used in the calculation of the carbon storage factor for cut-back asphalt. The storage factor for emulsified asphalt was provided by Alan James of Akzo Nobel Coatings, Inc. (James 2000).

Uncertainty

The principal source of uncertainty is that the available data are from short-term studies of emissions associated with the production and application of asphalt. As a practical matter, the cement in asphalt deteriorates over time, contributing to the need for periodic re-paving. Whether this deterioration is due to physical erosion of the cement and continued storage of carbon in a refractory form or physicochemical degradation and eventual release of CO₂ is uncertain. Long-term studies may reveal higher lifetime emissions rates associated with degradation.

Many of the values used in the analysis are also uncertain and are based on estimates and professional judgement. For example, the asphalt cement input for HMA was based on expert advice indicating that the range is variable—from about 3 to 5 percent—with actual content based on climate and geographical factors (Connolly 2000). Over this range, the effect on the calculated carbon storage factor is minimal (on the order of 0.1 percent). Similarly, changes in the assumed carbon content of asphalt cement would have only a minor effect.

The consumption figures for cut-back and emulsified asphalts are based on information reported for 1994. More recent trends indicate a decrease in cut-back use due to high VOC emission levels and a related increase in emulsified asphalt use as a substitute. However, because the carbon storage factor of each is 100 percent, use of more recent data would not affect the overall result.

Lubricants

Lubricants are used in industrial and transportation applications. They can be subdivided into oils and greases, which differ in terms of physical characteristics (e.g., viscosity), commercial applications, and environmental fate. According to EIA (2000), the carbon content of U.S. production of lubricants in 1999 was approximately 28 Tg CO₂ Eq. Based on apportioning oils and greases to various environmental fates, and characterizing those fates as resulting in either long-term storage or emissions, the overall carbon storage factor was estimated to be 9 percent; thus, storage in 1999 was about 3 Tg CO₂ Eq.

Methodology

For each lubricant category, a storage factor was derived by identifying disposal fates and applying assumptions as to the disposition of the carbon for each practice. An overall lubricant carbon storage factor was calculated by taking a production weighted average of the oil and grease storage factors.

Oils

Regulation of used oil in the United States has changed dramatically over the past 15 years.⁷ The effect of these regulations and policies has been to restrict landfilling and dumping, and to encourage collection of used oil. Given the relatively inexpensive price of crude oil, the economics have not favored re-refining—instead, most of the used oil that has been collected has been combusted.

Table B-11 provides an estimated allocation of the fates of lubricant oils, along with an estimate of the proportion of carbon stored in each fate. The ultimate fate of the majority of oils (about 84 percent) is combustion, either during initial use or after collection as used oil. Combustion results in 99 percent oxidation to CO₂, with correspondingly little long-term storage of carbon in the form of ash. Dumping onto the ground or into storm sewers, primarily by “do-it-yourselfers” who change their own oil, is another fate that results in conversion to CO₂ given that the releases are generally small and most of the oil is biodegraded. In the landfill environment, which tends to be anaerobic, at least for municipal landfills, it is assumed that 90 percent of the oil persists in an undegraded form. Re-refining adds a recycling loop to the fate of oil; it was assumed that about 97 percent of the carbon in re-refined oil is ultimately oxidized. Because of the dominance of fates that result in eventual release as CO₂, only about 3 percent of the carbon in oil lubricants goes into long-term storage.

Table B-11: Commercial and Environmental Fate of Oil Lubricants (Percent)

Fate of Oil	Portion of Total	
	Oil	Carbon Stored
Combusted During Use	20	1
Not Combusted During Use	80	-
Combusted as Used Oil*	64	1
Dumped on the ground or in storm sewers	6	0
Landfilled	2	90
Re-refined into lube oil base stock and other products	8	3
Weighted Average	-	2.9

* (e.g., in boilers or space heaters)

- Not applicable

Greases

Table B-12 provides analogous estimates for lubricant greases. Unlike oils, grease is generally not combusted during use, and combustion for energy recovery and re-refining are thought to be negligible. Although little is known about the fate of waste grease, it was assumed that 90 percent of the non-combusted portion is landfilled, and the remainder is dumped onto the ground or storm sewers. Because much of the waste grease will be in containers that render it relatively inaccessible to biodegradation, it was assumed that 90 percent and 50 percent of the carbon in landfilled and dumped grease, respectively, would be stored. The overall storage factor is 82 percent for grease.

Table B-12: Commercial and Environmental Fate of Grease Lubricants (Percent)

Fate of Grease	Total Grease	Carbon Stored
Combusted During Use	5	1
Not Combusted During Use	95	-
Landfilled	85.5	90
Dumped on the ground or in storm sewers	9.5	50
Weighted Average	-	81.8

- Not applicable

Having derived separate storage factors for oil and grease, the last step was to estimate the weighted average for lubricants as a whole. No data were found apportioning the mass of lubricants into these two categories, but the U.S. Census Bureau does maintain records of the value of production of lubricating oils and lubricating

⁷ For example, the U.S. EPA “RCRA (Resource Conservation and Recovery Act) On-line” web site (<http://www.epa.gov/rcraonline/>) has over 50 entries on used oil regulation and policy for 1994 through 2000.

greases. Assuming that the mass of lubricants can be allocated according to the proportion of value of production (92 percent oil, 8 percent grease), applying these weights to the storage factors for oils and greases (3 percent and 82 percent) yields an overall storage factor of 9 percent.

Data Sources

The estimate of the volume of lubricants produced annually is based on statistics provided by EIA (2000), which conducts surveys of the oil and grease consumption.

The characterization of fate is based primarily on professional judgement of an EPA regulatory analyst with experience in used oil (Rinehart 2000). For the proportions combusted, one percent was assumed to remain unoxidized in combustion processes (EIIIP 1999); for other fates, estimates are based on professional judgement. The assumption that landfilled oil and grease results in 90 percent storage is based on analogy with the persistence of petroleum in native petroleum-bearing strata, which are both essentially anaerobic. The assumption that oil dumped on the ground or in storm sewers is completely degraded is based on the observation that landfarming—application to soil—is one of the most frequently used methods for degrading refinery wastes. The lower degradation rate for grease is based on the observation that greases contain longer chain paraffins, which are more persistent. Re-refined oil was assumed to have a storage factor equal to the weighted average for the other fates (i.e., after re-refining, the oil would have the same probability of combustion, landfilling, or dumping as virgin oil).

Information on the value of production for oils and greases was obtained from reports by the U.S. Census Bureau (1999).

Uncertainty

The principal sources of uncertainty are the estimates of the commercial use, post-use, and environmental fate of lubricants, which, as noted above, are largely based on assumptions and judgement. There is no comprehensive system to track used oil and greases, which makes it difficult to develop a verifiable estimate of the commercial fates of oil and grease. The environmental fate estimates for percent of carbon stored are somewhat less uncertain, but also introduce uncertainty in the estimate.

The assumption that the mass of oil and grease can be divided according to their value also introduces uncertainty. Given the rather large difference between the storage factors for oil and grease, changes in their share of total lubricant production has a fairly large effect on the weighted storage factor.