Background Document for Life-Cycle Greenhouse Gas Emission Factors for Clay Brick Reuse and Concrete Recycling

EPA530-R-03-017
November 7, 2003

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I. EXECUTIVE SUMMARY

This paper describes the methodology and data sources used to develop greenhouse gas (GHG) emission factors for reused[1] clay bricks and recycled concrete. The emission factors presented below are the latest in a series of emission factors developed by the U.S. Environmental Protection Agency (EPA). EPA's research into the link between GHG emissions and waste management began in 1994 and continues today. In 1998, EPA published *Greenhouse Gas Emissions from Selected Materials in Municipal Solid Waste*, which presented the methodology for conducting a life-cycle assessment of the GHG impacts of waste management for commonly-recycled materials in the municipal solid waste stream. The key results of the report included life-cycle GHG emission factors for 12 materials and 5 waste management options: source reduction, recycling, composting, combustion, and landfilling. These emission factors were the basis for a user-friendly spreadsheet tool called the WAste Reduction Model (WARM). WARM was designed to assist waste managers in quantifying the GHG benefits of their waste management practices.

As research on life-cycle impacts of waste management practices on these and other materials progressed, it became necessary to update both the report and WARM. Both were updated to include: (1) new data on energy and recycling loss rates, (2) an improved analysis of the GHG benefits of composting, (3) emission factors for several new material types and new categories of mixed materials, (4) new energy data for the calculation of utility offsets, (5) revised carbon coefficients and fuel mixes for national average electricity generation, and (6) updated information on landfill gas recovery practices. The revised report, published in 2002, is entitled *Solid Waste Management and Greenhouse Gases: A Life Cycle Assessment of Emissions and Sinks*,[2] and covers 16 individual materials found in the municipal solid waste stream (e.g., aluminum cans, newspaper, dimensional lumber) and 7 categories of mixed materials (e.g., mixed paper, mixed plastics).[3]

All emission factors included in the first and second versions of the report have focused on either specific materials (e.g., steel cans) or mixed materials (e.g., mixed recyclables). In 2001, EPA began investigating the feasibility of developing emission factors for materials outside the municipal solid waste stream. This paper describes the methods EPA used to apply the life-cycle approach presented in the 1998 and 2002 reports to two construction materials: clay bricks and recycled concrete. The complexity of these emission factors necessitated a separate report documenting the methodology, data sources, and assumptions we used.

EPA's interest in clay bricks and concrete is derived from a growing interest in environmentally-friendly or "green" building practices, including reusing and recycling the impressive quantities of construction and demolition (C&D) debris that are generated each year. EPA estimates that 136 million tons[4] of C&D waste were generated in 1996. In 2001, the US produced over 8.3 billion clay bricks.[5] Concrete, composed of cement, water, and coarse and fine aggregates, is a high-volume, low-cost material that is used in extremely large quantities. Approximately 970 million tons of concrete were produced in 2000[6] and approximately 200 million tons of waste concrete[7] are generated annually from C&D and public works projects.

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[1] To maintain consistency with our other reports, the reuse of clay bricks may be referred to as "source reduction." Reusing clay bricks reduces the need for brick production, in effect causing source reduction. However, it is important to note that, unlike in reference to other materials, the term "source reduction" does not imply a fewer number of bricks actually being used.

[2] U.S. EPA 2002a. *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks*, U.S. Environmental Protection Agency, June 2002. EPA530-R-02-006.

[3] Report is available online at the following website: www.epa.gov/epaoswer/non-hw/muncpl/ghg/greengas.pdf.

[4] In this report, the term "ton" refers to short tons. Metric tons are specifically denoted as "metric tons."

[5] U.S. Census Bureau 2002. "Clay Construction Products: 2001," October 2002.

[6] The total consumption of cement in 2000 was 120,700,000 tons. It was assumed that 100 percent of this cement was used to make concrete and the concrete contained 12.5 percent cement by weight, resulting in a calculated concrete production of 970 million tons. Sources: Consumption data from Van Oss, Hendrik G. 2001. *Minerals Yearbook - Cement, 2000.* U.S. Geological Survey; cement content data from Collins 2002, personal communication between Terry Collins of Portland Cement Association and Philip Groth of ICF Consulting, 2002.

[7] Derived from: (1) Turley 2002, personal communication between William Turley of Construction Materials Recycling Association and Philip Groth of ICF Consulting, 2002; (2) Wilburn and Goonan 1998, "Aggregates from natural and recycled

Two emission factors were developed for clay bricks: source reduction (reuse) and landfilling. Similarly, two emission factors were developed for concrete: recycling and landfilling. The emission factor for source reducing clay bricks was calculated as the avoided GHG emissions from the manufacture of virgin bricks, including process energy (pre-combustion and combustion), transportation energy, and process non-energy emissions. The recycling emission factor for recycled concrete represents the GHG impacts of displacing virgin inputs with recycled inputs. Landfilling emission factors for clay bricks and concrete were based solely on transportation-related emissions, since neither clay bricks nor concrete generate methane (CH_4) when disposed in a landfill. The cement portion of concrete is capable of sequestering small amounts of carbon when placed in landfills. However, for reasons discussed below, this effect was not included in the landfill emission factor.

The primary source of data used in the creation of clay brick emission factors was life-cycle research conducted by Athena Sustainable Materials Institute in 1998. The concrete emission factors were derived from two main sources: the U.S. Census Bureau's 1997 Economic Census and *Aggregates from Natural and Recycled Sources*, a U.S. Geological Survey Circular by David Wilburn and Thomas Goonan. All of the information and data that was utilized in developing the GHG emission factors for clay brick and concrete is included in exhibits and appendices throughout this report.

Emission factors for clay bricks and concrete are presented in Exhibit 1 in metric tons of carbon equivalent per ton of product (MTCE/ton). These emission factors are comparable to factors presented in Exhibit ES-4 of the 2002 EPA report. Although the emission factors for clay bricks and recycled concrete are lower than for some other materials, the potential for emission reductions is significant due to the high volume of these materials discarded each year. Estimates of potential emission reductions by material type are presented in Exhibit 2.

Exhibit 1. GHG Emission Factors for Selected Materials and Waste Management Practices (MTCE/Ton)

Material	Net Source Reduction (Reuse) Emissions For Current Mix of Inputs	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions
Clay Bricks	(0.0788)	NA	NA	NA	0.0105
Concrete	NA	(0.0021)[a]	NA	NA	0.0105

NA – Not Available.
a. Assumes a transportation distance of 30 miles for virgin aggregate and 15 miles for recycled aggregate. This assumption is discussed in greater detail below.
Source: U.S. EPA 2002a.

Exhibit 2. Potential GHG Emissions Associated with Various Building Materials

Material	Estimated Annual Discards (tons)	Source Reduction: Emission Reduction Potential (MTCE)	Recycling: Emission Reduction Potential (MTCE)
Clay Bricks	NA	NA	NA
Concrete	200,000,000[a]	NA	(420,000)

NA – Not Available.
a. Source: Derived from Turley 2002 and Wilburn, et al. 1998.

sources—Economic assessments for construction applications," U.S. Geological Survey Circular 1176. Available online at greenwood.cr.usgs.gov/pub/circulars/c1176/c1176.html.

II. CLAY BRICKS

Bricks are produced by firing materials such as clay, kaolin, fire clay, bentonite, or common clay and shale. The majority of the bricks produced in the US are clay, accounting for an annual production of approximately 8.3 billion bricks. [8]

This report focuses on the source reduction of bricks that occurs when consumers reuse salvaged bricks rather than using new bricks. This report *does not* address the benefit of grinding and reusing broken or damaged bricks during the manufacturing process.

To estimate GHG emissions associated with municipal solid waste (MSW) management options, we analyzed whether the baseline scenario should include a mix of both virgin and recycled inputs. Athena discusses the use of sewage sludge, contaminated soils, and fly ash when making clay bricks, but does not provide values that could be useful for calculating a current mix estimate. It describes these practices as feasible, but not widely practiced at this time. Athena also notes that 4-8 percent of the volume of raw materials used in brick production is comprised of damaged, finished ware that has been recycled back into raw materials. Because these inputs reflect pre-consumer recycling, not post-consumer recycling, the energy associated with manufacturing brick with these inputs would still be considered "virgin" in our nomenclature. Based on the information provided by Athena, it appears that there is very little (if any) recycled-content brick being produced. Therefore, we assumed that virgin production is the same as production using the current mix (nearly 100 percent virgin inputs).

The following sections describe how we used information on clay bricks to develop life-cycle GHG emission factors for source reduction and landfilling.

Source Reduction (Reuse)

Source reduction activities reduce the demand for production of clay bricks, and consequently, reduce GHG emissions associated with brick production. Because reused bricks may lack the strength and durability of new bricks, the reuse of bricks is not appropriate for all brick structures. This is why the US Green Building Council (USGBC) recommends that reused bricks not be used in exterior structures in cold climates, as cold temperatures can exacerbate existing weaknesses in reused brick.[9] Clay bricks are sometimes reused in such decorative applications as brick fireplaces, hearths, patios, etc.

The GHG benefits of source reduction are calculated as the avoided emissions from the raw materials acquisition and manufacture of clay bricks. The energy used in these processes is primarily fossil fuel derived, resulting in GHG emissions. In addition, energy is required to obtain the fuels that are ultimately used in brick manufacturing (i.e., precombustion energy). The calculation of avoided GHG emissions for clay bricks was broken up into two components: process energy and transportation energy. Exhibit 3 presents emissions associated with these components, as well as the net GHG emission factor for source reduction. The following sections provide a summary of the data and calculations used to estimate process and transportation-related emissions. Appendix A provides all raw data and more detailed information on the genesis of these numbers.

Exhibit 3. Clay Brick Source Reduction (Reuse) Emission Factor (MTCE/Ton)

(a) Process Energy	(b) Transportation Energy	(c) Net Emissions (=a + b)
0.0782	0.0006	0.0788

[8] U.S. Census Bureau 2002. "Clay Construction Products: 2001," October 2002.
[9] Webster, Mark 2002. "The Use of Salvaged Structural Materials in New Construction," presentation posted on the US Green Building Council website, http://www.usgbc.org/expo2002/schedule/powerpoints/WS604_Webster_P461.pdf, November 2002.

Avoided Process Energy

In clay brick manufacturing, energy is required to obtain raw materials and to operate manufacturing equipment, as well as to extract and refine the fuels used in the brick manufacturing process (i.e., "pre-combustion" energy). Process energy GHG emissions result from both the direct combustion of fossil fuels and the upstream emissions associated with electricity use. To estimate process emissions, we first obtained an estimate of the total energy required to produce one ton of clay bricks, which is reported as 5.1 million Btu.[10] Next, we determined the distribution of fuels that comprise this Btu estimate. Using this information, we then multiplied each fuel's Btu estimate by each fuel's carbon content to obtain carbon dioxide (CO_2) emissions for each fuel. The carbon coefficients we used are presented in Exhibit 4. We then conducted a similar analysis for fugitive CH_4 emissions, using fuel-specific CH_4 coefficients. Finally, total process energy GHG emissions were calculated as the sum of GHG emissions, including both CO_2 and CH_4, from all the fuel types used in the production of one ton of clay bricks. The calculations for process energy emissions from manufacturing clay bricks are provided in Exhibit 4. As the exhibit shows, the process energy for clay bricks results in 0.078 MTCE per ton of clay bricks produced.

Exhibit 4. Process Energy Emissions Calculations for Virgin Clay Brick

Fuel Type	**(a)** **Percent of Total Btu**[a]	**(b)** **Million Btu used for Clay Brick Production (=5.1008 x a)**	**(c)** **Fuel-specific Carbon Coefficient (MTCE/ Million Btu)**[b]	**(d)** **Fugitive CH_4 Emissions MTCE/Million Btu**	**(e)** **Process Energy CO_2 Emissions (MTCE/Ton) (=b x c)**	**(f)** **Process Energy CH_4 Emissions (MTCE/Ton) (=b x d)**	**(g)** **Total Process Energy Emissions (MTCE/Ton) (=e + f)**
Diesel	1.89%	0.0963	0.0199	0.0001	0.0019	<0.0001	0.0019
National Average Fuel Mix for Electricity	39.38%	2.0087	0.0158	0.0006	0.0317	0.0012	0.0329
Natural Gas	58.73%	2.9958	0.0138	0.0007	0.0413	0.0021	0.0434
Total	**100%**	**5.1008**	**n/a**	**n/a**	**0.0749**	**0.0033**	**0.0782**

n/a – not applicable.
a. Calculated using fuel-specific Btu data provided in Appendix A.
b. The electricity emission factor was calculated from a weighted average of fuels used in energy production in the US.
Source: EIA 2001. *Annual Energy Review: 2000*, U. S. Department of Energy, EIA. August 2001.
Note: Totals may not sum due to independent rounding.

Transportation Energy

Transportation energy GHG emissions result from the combustion of fossil fuels to transport raw materials used in the manufacture of clay brick as well as energy used to extract and refine the fuels used during transport.[11] The methodology for estimating transportation energy GHG emissions is similar to the methodology for process emissions. Based upon an estimate of total clay brick transportation energy and the corresponding fuel mix, we calculated total transportation energy emissions using fuel-specific coefficients for CO_2 and CH_4. The result is a transportation GHG emission factor of 0.0006 MTCE per ton of clay bricks, as shown in Exhibit 5.

[10] This total represents the sum of pre-combustion and combustion process energy.
[11] Note: As with other materials for which we have developed GHG emission factors, transportation of finished goods to consumers was not included in the analysis.

Exhibit 5. Transportation Energy Emissions Calculations for Virgin Clay Brick

Fuel Type	(a) Percent of Total Btu[a]	(b) Million Btu used for Clay Brick Transport (=0.031 x a)	(c) Fuel-specific Carbon Coefficient (MTCE/ Million Btu)	(d) Fugitive CH_4 Emissions MTCE/Million Btu	(e) Transport Energy CO_2 Emissions (MTCE/Ton) (=b x c)	(f) Transport Energy CH_4 Emissions (MTCE/Ton) (=b x d)	(g) Total Transport Energy Emissions (MTCE/Ton) (=e + f)
Diesel	100	0.0307	0.0199	0.0001	0.0006	<0.0001	0.0006
Total	**100**	**0.0307**	**n/a**	**n/a**	**0.0006**	**<0.0001**	**0.0006**

n/a – not applicable.
a. Calculated using fuel-specific Btu data provided in Appendix A.

Recycling

Our research indicated that there is very little, if any, post-consumer recycling of clay bricks; therefore, we have not developed an emission factor for recycling them.

Combustion

As clay bricks are not combusted, we did not develop emission factors for this waste management option.

Landfilling

Typically, the emission factor for landfilling is comprised of four parts: landfill CH_4 emissions, CO_2 emissions from transportation and landfill equipment operation, landfill carbon storage, and avoided utility emissions. However, as with other inorganic materials for which EPA has developed emission factors, there are no CH_4 emissions, carbon storage, or avoided utility emissions associated with landfilling clay bricks. As a result, the emission factor for landfilling represents the CO_2 emissions associated with combusting diesel fuel to collect the waste and operate the landfill equipment. These emissions were estimated at 0.01 MTCE per ton of clay bricks landfilled[12] based on the default landfill transportation data used for other materials in the EPA 2002 report.

[12] Landfill data obtained from FAL 1994. *The Role of Recycling in Integrated Solid Waste Management for the Year 2000*, Franklin Associates, Ltd., (Stamford, CT: Keep America Beautiful, Inc.) September 1994, p. I-5.

III. CONCRETE

Concrete is a high-volume building material produced by mixing cement, water, and coarse and fine aggregates. Its use is nearly universal in modern construction as it is an essential component of roads, foundations, high-rises, dams, and other staples of the developed landscape. This section presents the methodology used to estimate the life-cycle GHG impacts of end-of-life waste management options for concrete. Approximately 200 million tons of waste concrete are produced each year through C&D projects, while nearly five times that amount is used annually in new construction projects. Currently, an estimated 50 to 60 percent of waste concrete is recycled, while the remainder is landfilled.[13]

The following sections describe how we used information on the processes associated with recycling and landfilling concrete to develop life-cycle GHG emission factors for recycling and landfilling.

Source Reduction

Although concrete may be re-used or used in ways that could reduce the overall demand for new concrete structures, the benefits of this type of activity have not yet been quantified.

Recycling

When structures are demolished, the waste concrete can be crushed and reused in place of virgin aggregate. Doing so reduces the GHG emissions associated with producing concrete using virgin aggregate material. Virgin aggregates, which include crushed stone, gravel, and sand, are used in a wide variety of construction applications, such as road base, fill, and as an ingredient in concrete and asphalt pavement. Over 2 billion tons of aggregates are consumed each year in the US, with an estimated 5 percent coming from recycled sources such as asphalt pavement and concrete.[14]

While precise statistics regarding the current recycling rate for concrete are difficult to obtain, a 1997 estimate by the Construction Materials Recycling Association (CMRA), suggests that approximately 107 million tons of concrete were recycled in 1996.[15] The USGS estimates that of the concrete recycled in 1997, at least 83 percent was used in applications that typically employ virgin aggregate: 68 percent of all recycled product was used as road base, 9 percent in asphalt hot mixes, and 6 percent in new concrete mixes. Non-aggregate uses of recycled concrete included 7 percent as general fill, 3 percent as high-value riprap, and 7 percent as other.[16] As tipping fees at landfills increase in many urban areas and recycling techniques continue to improve, concrete recycling is expected to become even more popular. EPA hopes that the GHG emission factor for concrete can be used to characterize the benefits of these increased recycling efforts.

Unlike many of the other materials for which EPA has developed GHG emission factors (e.g., aluminum cans, glass bottles), concrete is assumed to be recycled in an "open loop" – i.e., concrete is recycled into a product other than itself, namely aggregate.[17] Therefore, the GHG benefit of concrete recycling results from the avoided emissions associated with mining and processing aggregate that concrete is replacing.[18]

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[13] Derived from Turley 2002 and Wilburn, et al. 1998.
[14] USGS 2000. "Recycled Aggregates—Profitable Resource Conservation." USGS Fact Sheet FS–181–99.
[15] Turley 2002.
[16] USGS 2000.
[17] Concrete may be recycled in a "closed-loop" by being crushed and reused as aggregate in new concrete. The recycling process is believed to rehydrate some cement in the used concrete, thus reducing the need for cement in the new concrete, resulting in additional GHG benefits. However, sufficient data to quantify this additional benefit is not available at this point.
[18] There is evidence that recycled concrete would also have the benefit of increased carbon storage. Studies have shown that over time, the cement portion of concrete can absorb CO_2. Factors such as age, cement content, and the amount of exposed surface area affect the rate of carbon absorption. While it is likely that the increase in surface area due to crushing would increase the rate of CO_2 absorption, insufficient data exists at this time to quantify this benefit.

The GHG benefits of recycling are calculated by comparing the difference in emissions associated with producing and transporting a ton of virgin aggregate versus producing and transporting a comparable amount of recycled inputs (i.e., crushed concrete). The GHG emissions associated with these steps result from the consumption of fossil fuels used in the production and transport of aggregate (combustion energy), as well as the upstream energy (pre-combustion energy) required to obtain these fuels. The calculation of avoided GHG emissions for concrete aggregate was broken up into two components: process energy and transportation energy emissions. Exhibit 6 presents these results, as well as the net GHG emission factor for recycling. The remainder of this section describes the steps that were taken to calculate the GHG impacts of recycling concrete. Appendix B presents the raw data utilized in these calculations.

Exhibit 6. Concrete Recycling Emission Factor (MTCE/Ton)

(a) Process Energy Emissions	(b) Transportation Energy Emissions	(c) Net Emissions (=a + b)
-0.0003	-0.0019	-0.0021

Note: Totals may not sum due to independent rounding.

To calculate the benefit of recycling concrete to displace virgin aggregate, the following steps were necessary:

Step 1: Calculate the emissions for virgin production of one ton of aggregate.

Step 2: Calculate the emissions associated with processing and delivering a comparable amount of recycled concrete to be used in place of virgin aggregate.

Step 3: Calculate the difference in emissions between recycled and virgin scenarios.

These steps are described in more detail as follows:

Step 1. Calculate the emissions for virgin production of one ton of aggregate. Process energy is required to extract and process raw materials. Transportation energy GHG emissions result from the combustion of fossil fuels to transport virgin aggregate to the job site where it is used. Although previous emission factors did not consider emissions associated with transporting the virgin or recycled materials to the consumer, in the case of aggregates, these emissions are a driving factor in the GHG impacts of waste concrete management options. For the calculation of this emission factor, we assumed that virgin aggregates must be transported 30 miles[19] to the end user. Because it is a major driver of the final emission factor, this assumption is discussed at greater length in Step 3.

As discussed above in the Source-Reducing Clay Brick section, emissions from both process and transportation energy emissions are calculated by applying fuel-specific carbon and fugitive CH_4 emissions coefficients to energy data for aggregate production and transportation. The calculations for virgin process and transportation emissions for aggregate are shown in Exhibits 7 and 8. As the exhibits show, the process and transportation energy emissions for virgin aggregate are estimated as 0.0009 and 0.0037 MTCE per ton of aggregate produced, respectively.

[19] Nisbet, M.A., M.G. VanGeem, J. Gadja, and M.L. Marceau. 2000. *Environmental Life Cycle Inventory of Portland Cement Concrete.* Portland Cement Association, Skokie, Illinois, PCA R&D Serial No. 2137.

Exhibit 7. Process Energy Emissions Calculations for Virgin Aggregate

Fuel Type	(a) Percent of Total Btu[a]	(b) Million Btu used for Aggregate Production (=0.0486 x a)	(c) Fuel-specific Carbon Coefficient (MTCE/ Million Btu)[b]	(d) Fugitive CH_4 Emissions MTCE/Million Btu[b]	(e) Process Energy CO_2 Emissions (MTCE/Ton) (=b x c)	(f) Process Energy CH_4 Emissions (MTCE/Ton) (=b x d)	(g) Total Process Energy Emissions (MTCE/Ton) (=e + f)
Gasoline	3.16	0.0015	0.0192	0.0001	<0.0001	<0.0001	<0.0001
Distillate Fuel	60.42	0.0293	0.0199	0.0001	0.0006	<0.0001	0.0006
Residual Fuel	5.68	0.0028	0.0214	0.0001	0.0001	<0.0001	0.0001
National Average Fuel Mix for Electricity	22.61	0.0110	0.0158	0.0006	0.0002	<0.0001	0.0002
Coal Used by Industry (Non-Coking Coal)	1.40	0.0007	0.0251	0.0009	<0.0001	<0.0001	<0.0001
Natural Gas	6.74	0.0033	0.0138	0.0007	<0.0001	<0.0001	<0.0001
Total	**100**	**0.0486**	**n/a**	**n/a**	**0.0009**	**<0.0001**	**0.0009**

n/a – not applicable.
a. Calculated using fuel-specific Btu data provided in Appendix B.
b. The electricity emission factor was calculated from a weighted average of fuels used in energy production in the US. Source: EIA 2001.
Note: Totals may not sum due to independent rounding.

Exhibit 8. Transportation Energy Emissions Calculations for Virgin Aggregate

Fuel Type	(a) Percent of Total Btu[a]	(b) Million Btu used for Aggregate Transport (=0.1869 x a)	(c) Fuel-specific Carbon Coefficient (MTCE/ Million Btu)	(d) Fugitive CH_4 Emissions MTCE/Million Btu	(e) Transport Energy CO_2 Emissions (MTCE/Ton) (=b x c)	(f) Transport Energy CH_4 Emissions (MTCE/Ton) (=b x d)	(g) Total Transport Energy Emissions (MTCE/Ton) (=e + f)
Diesel Fuel	100.00	0.1869	0.0199	0.0001	0.0037	<0.0001	0.0037
Total	**100.00**	**0.1869**	**n/a**	**n/a**	**0.0037**	**<0.0001**	**0.0037**

n/a – not applicable.
a. Calculated using fuel-specific Btu data provided in Appendix B.

<u>Step 2. Calculate the emissions for processing and delivery of one ton of recycled aggregate (i.e., crushed cement).</u> As with virgin aggregate, emissions from both process and transportation energy emissions are calculated by applying fuel-specific carbon and fugitive CH_4 emissions coefficients to energy data for aggregate production and transportation. For the calculation of this emission factor, we assumed that recycled aggregate (i.e., waste concrete) must be transported 15 miles to the end user. The calculations for recycled process and transportation emissions for aggregate are shown in Exhibits 9 and 10. As the exhibits show, the process and transportation energy for recycled aggregate are estimated as 0.0006 and 0.0019 MTCE per ton of aggregate produced, respectively.

Exhibit 9. Process Energy Emissions Calculations for Recycled Aggregate

Fuel Type	(a) Percent of Total Btu[a]	(b) Million Btu used for Aggregate Production (=0.0352 x a)	(c) Fuel-specific Carbon Coefficient (MTCE/ Million Btu)[b]	(d) Fugitive CH_4 Emissions MTCE/Million Btu[b]	(e) Process Energy CO_2 Emissions (MTCE/Ton) (=b x c)	(f) Process Energy CH_4 Emissions (MTCE/Ton) (=b x d)	(g) Total Process Energy Emissions (MTCE/Ton) (=e + f)
Diesel Fuel	50%	0.0176	0.0199	0.0001	0.0003	<0.0001	0.0004
National Average Fuel Mix for Electricity	50%	0.0176	0.0158	0.0006	0.0003	<0.0001	0.0003
Total	**100%**	**0.0352**	**0.0357**	**0.0007**	**0.0006**	**<0.0001**	**0.0006**

n/a – not applicable.
a. Calculated using fuel-specific Btu data provided in Appendix B.
b. The electricity emission factor was calculated from a weighted average of fuels used in energy production in the US.
Source: EIA 2001.
Note: Totals may not sum due to independent rounding.

Exhibit 10. Transportation Energy Emissions Calculations for Recycled Aggregate

Fuel Type	(a) Percent of Total Btu[a]	(b) Million Btu used for Aggregate Transport (=0.0935 x a)	(c) Fuel-specific Carbon Coefficient (MTCE/ Million Btu)	(d) Fugitive CH_4 Emissions MTCE/Million Btu	(e) Transport Energy CO_2 Emissions (MTCE/Ton) (=b x c)	(f) Transport Energy CH_4 Emissions (MTCE/Ton) (=b x d)	(g) Total Transport Energy Emissions (MTCE/Ton) (=e + f)
Diesel	100%	0.0935	0.0199	0.0001	0.0019	<0.0001	0.0019
Total	**100%**	**0.0935**	**n/a**	**n/a**	**0.0019**	**<0.0001**	**0.0019**

n/a – not applicable.
a. Calculated using fuel-specific Btu data provided in Appendix B.

Step 3. Calculate the difference in emissions between virgin and recycled production. The GHG savings associated with recycling were then calculated by subtracting the virgin emissions estimate from the recycled emissions estimate using the results from Steps 1 and 2. The results are shown in Exhibit 11.

Exhibit 11. Aggregate Recycling Emission Factor (MTCE/Ton)

	(a) Process Energy Emissions	(b) Transportation Energy Emissions	(c) Total (a + b)
Recycled Manufacture	0.0006	0.0019	0.0025
Virgin Manufacture	0.0009	0.0037	0.0047
Total (Recycled - Virgin)	**-0.0003**	**-0.0019**	**-0.0021**

Note: Totals may not sum due to independent rounding.

Because these results are extremely sensitive to assumptions regarding transportation distances for virgin and recycled aggregate, we have also expressed the net emission factor for recycling as a function of the difference in transportation distance between recycled and virgin aggregate:

Net Recycling Emissions (MTCE/ton) = $1.0 \times 10^{-4} \times D_{Net} - 2.7 \times 10^{-4}$

Where D_{Net} = the distance in miles for transporting recycled aggregate – the distance in miles for transporting recycled aggregate.

By solving the equation for D, the difference in transportation distance between recycled and virgin aggregate, we find that the break-even value for D is approximately 3 miles. Therefore, recycled aggregate will result in GHG savings as long as it is transported no more than 3 miles further than virgin aggregate. Even greater GHG savings will occur if the recycled aggregate is transported less than the virgin material. As developed areas continue to deplete and/or develop over local sources of aggregate, virgin aggregate must be transported from ever-greater distances. Conversely, waste concrete will more commonly be generated in developed areas, where it may be recycled and reused locally.

Combustion

As concrete is not combusted, we did not develop an emission factor for this waste management option.

Landfilling

Typically, the emission factor for landfilling is comprised of four parts: landfill CH_4, CO_2 emissions from transportation and landfill equipment operation, landfill carbon storage, and avoided utility emissions. However, as with other inorganic materials for which EPA has developed emission factors, there are no CH_4 emissions, or avoided utility emissions associated with landfilling concrete. Studies have indicated that over time, the cement portion of concrete is capable of absorbing CO_2.[20] The amount of carbon stored is affected by age, cement content, and the amount of exposed surface area. While this effect would represent landfill carbon storage when concrete is deposited in a landfill, the results of this with respect to the emission factor are difficult to quantify and beyond the scope of this report.

As a result, the emission factor for landfilling represents the CO_2 emissions associated with combusting diesel fuel to collect the waste and operate the landfill equipment. These emissions were estimated at 0.01 MTCE per ton of concrete landfilled[21] based on the same underlying data that was used for other materials in the EPA 2002 report.

[20] Gadja, John 2001. "Absorption of Atmospheric Carbon Dioxide by Portland Cement Concrete," Portland Cement Association, Skokie, Illinois, PCA R & D Serial No. 2255a.
[21] Landfill data obtained from FAL 1994.

IV. SUMMARY

The emission factors in this report are designed to help waste managers and others determine the GHG impacts of alternative waste management options for clay bricks and concrete. These factors are additions to the current factors described in the report, *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks*, available online at www.epa.gov/mswclimate/greengas.pdf. Readers are encouraged to consult this report for more background on how life-cycle analysis is used to develop emission factors.

In addition, these factors will be added to EPA's WARM model, which provides a user-friendly way of assessing the GHG impacts of alternative waste management practice. Users simply need to enter tonnage data for the baseline and alternative waste management options, and WARM will provide the emissions results. WARM also allows users to specify some of the assumptions driving the emission factors, such as the miles of travel required to transport discarded clay bricks and concrete to the landfill. WARM is available online at www.epa.gov/global warming/actions/waste/w-online.htm.

To apply these emission factors, one needs to compare the GHG results using a baseline and alternative waste management scenario. For each scenario, the GHG impact is calculated by multiplying the tonnage of clay bricks and concrete by the appropriate emission factor. For example, suppose a company is considering reusing its waste clay bricks instead of its current (baseline) practice of landfilling the bricks. If the company generated 100 tons of clay bricks, the GHG benefits of recycling versus landfilling could be calculated as follows:

$$[100 \text{ tons x } -0.08 \text{ MTCE/ton}_{\text{source reduction}}] - [100 \text{ tons x } 0.01 \text{ MTCE/ton}_{\text{landfilling}}] = -9 \text{ MTCE}$$

As the above equation shows, this one company could save 9 MTCE by reusing clay bricks instead of landfilling, equivalent to reducing gasoline use by nearly 3,800 gallons[22] each year.

When applying the emission factors at the national level, we can see the tremendous potential for GHG emission reductions. Exhibit 12 shows the current estimated concrete life-cycle GHG emissions assuming the current waste disposal scenario, as well as the potential reductions if all of the waste concrete was recycled into aggregate. As the exhibit shows, if all concrete was recycled, over 1 million MTCE would be avoided (i.e., -420,000 MTCE – 700,000 MTCE), equivalent to removing nearly 1 million cars from the road[23] for a year. Reliable data for current disposal and source reduction rates of clay bricks are unavailable; we were therefore unable to conduct a similar analysis for clay bricks.

Finally, we close by noting that although this analysis is based upon the best available life-cycle data, uncertainties exist in the final emission factors. It is important that we continue to assess the assumptions and data used to develop these emission factors. To the extent possible, EPA will attempt to reflect changes in the manufacturing processes, recycling processes, and disposal practices in subsequent versions of these emission factors. In addition, it should be noted that these results are designed to represent national average data. The actual GHG impacts of source reducing or recycling clay bricks and concrete, respectively, will vary depending on individual circumstances (e.g., transportation of waste concrete to construction site).

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[22] EPA 2003. Greenhouse Gas Equivalencies Calculator. Draft version.
[23] Ibid.

Exhibit 12. Current Baseline GHG Emissions and Reduction Potential for Concrete

		Baseline Disposal			Assume 100% Recycling		
Disposal Option	(a) EF (MTCE/ Ton)	(b) End of Life Fate (%)	(c) End of Life Fate (Tons)	(d) Net GHG Emissions (MTCE) (=a x c)	(e) End of Life Fate (%)	(f) End of Life Fate (Tons)	(g) Net GHG Emissions (MTCE) (=a x f)
Recycling	-0.0021	55%	110,000,000	-240,000	100%	200,000,000	-420,000
Landfilling	0.0105	45%	90,000,000	940,000	0%	0	0
Total	**n/a**	**100%**	**200,000,000**	**700,000**	**100%**	**200,000,000**	**-420,000**

n/a – not applicable.

a. As described at the beginning of the concrete section, we estimate that 50 to 60 percent of concrete is currently recycled. The analysis in this exhibit assumes a 55 percent recycling rate.

Appendix A. Data Used to Derive Clay Brick Source Reduction Emission Factor

Exhibit A-1: Energy Data for the Production of 1 Ton of Clay Bricks

	(a)	(b)	(c)
Fuel	**Combustion Energy per Ton[a] (million Btu)**	**Precombustion Energy per Ton[b] (million Btu)**	**Total Energy per Ton (million Btu) (=a + b)**
Process Energy Data			
Electricity	2.0087	0.0000	2.0087
Natural Gas	2.6724	0.3234	2.9958
Diesel	0.0813	0.0150	0.0963
Total	**4.7624**	**0.3384**	**5.1008**
Transportation Energy Data			
Diesel	0.0259	0.0048	0.0307
Total	**0.0259**	**0.0048**	**0.0307**

a. Athena 1998. *Life Cycle Analysis of Brick and Mortar Products,* The Athena Sustainable Materials Institute, September 1998.

b. "Precombustion" energy is calculated by multiplying the combustion energy by a fuel-specific scaling factor from EPA 1998 to account for upstream combustion energy required to obtain the fuels. Source: EPA 1998. *Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste*, U.S. Environmental Protection Agency, Office of Solid Waste.

Appendix B. Data Used to Derive Concrete Recycling Emission Factor

In order to calculate the recycling emission factor for concrete, the process energy for virgin aggregate was first determined by dividing total national energy consumption for the crushed stone industry, as reported in the U.S. Census Bureau's 1997 Economic Census, by the total production of crushed stone in 1997. We included three industry categories assumed to represent the aggregate industry. The raw data for these industries, listed by name and NAICS Industry Code, are presented in Exhibit B-1.

Exhibit B-1: National Consumption of Energy by the Crushed Stone Industry in Physical Units[a]

Material	NAICS Code	Coal (thousand tons)	Distillate Fuel Oil (thousand barrels)	Residual Fuel Oil (thousand barrels)	Gas (bcf)	Gasoline (million gallons)	Other ($1,000)	Undistributed ($1,000)	Electricity (million kwh)
Crushed & Broken Limestone Mining & Quarrying	212312	43	2,312	308	2	11	$2,458	$ 56,418	3,178
Crushed & Broken Granite Mining & Quarrying	212313	b	693	171	b	2	b	$ 6,003	738
Other Crushed & Broken Stone Mining & Quarrying	212319	-	468	60	2	2	$174	$ 20,770	725
Total		**43**	**3,474**	**540**	**4**	**15**	**$2,632**	**$ 83,191**	**4,642**

a. U.S Census Bureau 1997. "Fuels and Electric Energy Report," 1997 Economic Census.
b. Withheld to avoid disclosing data of individual companies.

Having determined total physical units, the next step was to convert physical units into million Btu. However, some of the energy consumption was reported as "Other" or "Undistributed," and thus reported in terms of expenditures on fuel, rather than physical units consumed. We will first calculate fuel consumption in million Btu for known units. These calculations are presented in Exhibit B-2.

Exhibit B-2: National Consumption of Energy by the Crushed Stone Industry in BTU

	(a) Consumption in Column b Units	(b) Units	(c) Heat Content[a] (million btu/unit)	(d) Energy Consumption (million btu) (a x c)
Coal	43	1000 tons	22,172	953,396
Distillate Fuel	3,474	1000 barrels	5,825	20,233,138
Residual Fuel	540	1000 barrels	6,287	3,392,465
Natural Gas	4	billion cubic feet	1,027,000	4,210,700
Gasoline	15	million gallons	125,071	1,838,550
Electricity	4,642	million kwh	3,412	15,837,480

a. Source: EIA 2001.

To calculate the consumption in million Btu for "other" and "undistributed" fuels, we made the assumption for this analysis that this fuel had a delivered fuel cost similar to distillate fuel oil. The delivered cost of distillate fuel was determined by dividing the cost of distillate fuel as reported in the *1997 Economic Census* by the distillate fuel consumed in million Btu. This calculation is illustrated in Exhibit B-3 as follows:

Exhibit B-3: Calculation of Delivered Cost of Distillate Fuel

(a) Cost of distillate fuel	(b) Consumption of distillate fuel (million Btu)	(c) Cost of distillate fuel ($/million Btu) (a/b)
$127,378,000	20,233,138	$5.54

Next, we calculated consumption of "other" and "undistributed" fuels using the expenditures on these fuels from Exhibit B-1 and the cost of distillate fuel from Exhibit B-3 as a proxy. This calculation is shown in Exhibit B-4:

Exhibit B-4: Calculation of Consumption of "Other" and "Undistributed" Fuels

(a) Cost of other fuel	(b) Cost of undistributed fuel	(c) Cost of distillate fuel ($/million Btu)	(d) Consumption of other and undistributed fuel (million Btu) =(a+b)/c
$2,632,000	$83,191,000	$5.54	15,491,597

Note: Totals may not sum due to independent rounding.

We then calculated the total production of aggregate in 1997 as reported in the U.S. Census Bureau's *1997 Economic Census.* These data are presented in Exhibit B-5.

Exhibit B-5: Production of Aggregate

Material	NAICS Code	Production (million tons)
Crushed & Broken Limestone Mining & Quarrying	2123120100	954.9
Crushed & Broken Granite Mining & Quarrying	2123130100	255.8
Other Crushed & Broken Stone		
Bituminous Limestone and Bituminous Sandstone	2123190111	3.3
Other Crushed and Broken Stone	2123190121	228.7
Total		**1442.7**

Finally, we are able to calculate fuel consumption in million Btu per ton of aggregate, using the energy consumption data from Exhibit B-2 and the aggregate production data from Exhibit B-5. Please note that "other" and "undistributed" fuel is reported under the distillate fuel calculated by adding the results of Exhibit B-4 to the distillate fuel consumption in million Btu reported in Exhibit B-2. During the calculation of the concrete recycling emission factor, we use the distillate fuel carbon coefficient as a proxy for "other" and "undistributed" fuels. The calculation of fuel consumption per ton of aggregate is presented in Exhibit B-6.

Exhibit B-6: Energy Consumption by Fuel, million Btu/ton virgin aggregate

Fuel	(a) Energy Consumption (million btu)	(b) Total Production of Aggregate (million tons)	(c) Energy Consumption (million Btu/ton) =(a/b) x 10^{-6}
Coal	953,396		0.0007
Distillate Fuel[a]	35,724,734		0.0248
Residual Fuel	3,392,465	**1442.7**	0.0024
Natural Gas	4,210,700		0.0029
Gasoline	1,838,550		0.0013
Electricity	15,837,480		0.0110
Total	**61,957,326**		**0.0429**

a. Includes "other" and "undistributed" fuel.

In order to be recycled as aggregate, concrete must be crushed to the appropriate size and rebar or other supportive steel must be removed. The recycled aggregate process energy was calculated using data from Wilburn and Goonan, 1998. According to their research, the energy required to recycle one ton of concrete was 34 million joules per ton, in the form of electricity and diesel fuel. For this analysis, we assumed that electricity and diesel were consumed in an equal proportion. The calculation of recycled aggregate process energy by fuel is presented in Exhibit B-7:

Exhibit B-7: Process Energy Consumption by Fuel, million Btu/ton recycled aggregate

	(a) Percentage by fuel	(b) Total Consumption (MJ/ton)	(c) million Btu/MJ	(d) Consumption by fuel (million Btu/ton aggregate) =a x b x c
Diesel	50%	34	0.0009478	0.0161
Electricity	50%		0.0009478	0.0161

The transportation energy for both virgin and recycled aggregate was calculated using the estimate from Wilburn and Goonan, 1998, that the transportation energy requirement for both is 3,800 joules/kilogram-kilometer. This value was then converted to million Btu/ton-mile and multiplied by the assumed transportation distances of 30 miles for virgin aggregate and 15 miles for recycled aggregate according to the methodology presented in Exhibit B-8.

Exhibit B-8: Transportation Energy Consumption, million Btu/ton-mile

	(a) Transportation Energy, Diesel Fuel (joules/kg-km)	(b) Conversions: million Btu/J	(c) Conversions: km/mile	(d) Conversions: kg/ton	(e) Converted Transportation Energy (million Btu/ton-mile) =a x b x c x d	(f) Transportation Distance (miles)	(g) Transportation Energy (million Btu/ton) =e x f
Virgin aggregate (crushed stone)	3,800	9.478E-10	1.609	908	0.0020	30	0.0610
Recycled aggregate	3,800					15	0.0305

The process and transportation energy for both virgin and recycled aggregate, as calculated in the previous 8 exhibits, are presented in the two following summary tables.

Exhibit B-9: Process Energy Data for the Production of One Ton of Virgin Aggregate

Fuel	(a) Combustion Energy (million Btu/ton)[a]	(b) Precombustion Energy (million Btu/ton)[b]	(c) Total Energy (million Btu/ton) (=a + b)
Process Energy			
Coal	0.0007	0.0000	0.0007
Distillate fuel oil	0.0248	0.0046	0.0293
Residual fuel oil	0.0024	0.0004	0.0028
Gas	0.0029	0.0004	0.0033
Gasoline	0.0013	0.0003	0.0015
Electricity	0.0110	0.0000	0.0110
Total	**0.0429**	**0.0056**	**0.0486**
Transportation Energy			
Diesel	0.1578	0.0292	0.1869
Total	**0.1578**	**0.0292**	**0.1869**

a. As calculated in Exhibits B-1 through B-6 and B-8.
b. "Precombustion" energy is calculated by multiplying the combustion energy by a fuel-specific scaling factor from EPA 1998 to account for upstream combustion energy required to obtain the fuels. Source: EPA 1998.

Exhibit B-10: Process Energy Data for the Production of One Ton of Recycled Aggregate

Fuel	(a) Combustion Energy (million Btu/ton)[a]	(b) Precombustion Energy (million Btu/ton)[b]	(c) Total Energy (million Btu/ton) (=a + b)
Process Energy			
Electricity	0.0161	0.0000	0.0161
Diesel	0.0161	0.0030	0.0191
Total	**0.0322**	**0.0030**	**0.0352**
Transportation Energy			
Diesel	0.0789	0.0146	0.0935
Total	**0.0789**	**0.0146**	**0.0935**

a. As calculated in Exhibits B-1 through B-6 and B-8.
b. "Precombustion" energy is calculated by multiplying the combustion energy by a fuel-specific scaling factor from EPA 1998 to account for upstream combustion energy required to obtain the fuels. Source: EPA 1998.

Appendix C. Conversion Factors Used in Calculations

Exhibit C-1. Conversions

Unit Conversions		
1 ton	=	0.9072 metric tons
1 metric ton	=	2,204.6226 pounds
1 ton	=	907.1847 kilograms
1 $MTCO_2$	=	44/12 MTCE
1 kilometer	=	1.6093 miles
1 Mega Joule	=	0.0009478 million Btu
Global Warming Potentials (GWPs)		
1 metric ton CH_4	=	1/21 $MTCO_2$

Exhibit C-2. Carbon Coefficients

Fuel	Metric Tons Carbon Equivalent (MTCE) from Combustion Per Million Btu	MTCE from Fugitive CH_4 Emissions Per Million Btu
Gasoline	0.01925	0.00010
LPG	0.01691	0.00010
Distillate Fuel	0.01987	0.00010
Residual Fuel	0.02141	0.00010
Diesel	0.01987	0.00010
National Average Fuel Mix for Electricity	0.01579	0.00059
Coal Used by Industry (Non-Coking Coal)	0.02510	0.00092
Petroleum Coke	0.02785	-
Natural Gas	0.01378	0.00070
Wastes	0.01942	0.00001

Exhibit C-3. Heat Content Factors

Fuel	Unit	Heat Content (million Btu/Unit)
Coal	1,000 tons	22,172
Distillate Fuel	1,000 barrels	5,825
Residual Fuel	1,000 barrels	6,287
Natural Gas	billion cubic feet	1,027,000
Gasoline	million gallons	125,071
Electricity	million kwh	3,412