Portland Cement Association

Research & Development Information

PCA R&D Serial No. 2464

Partial Environmental Life Cycle Inventory of an Insulating Concrete Form House Compared to a Wood Frame House

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KEYWORDS

Cement, concrete, emissions, embodied energy, energy, housing, ICF, insulating concrete forms, LCA, life cycle assessment, LCI, life cycle inventory, life cycle, modeling, residential, wood

ABSTRACT

A partial life cycle inventory (LCI) of a wood frame house and an insulating concrete form (ICF) house has been carried out according to the Society of Environmental Toxicology and Chemistry (SETAC) guidelines and the International Organization for Standardization (ISO) standards 14040 and 14041. The houses were modeled in five cities, representing a range of U.S. climates: Phoenix, Miami, Washington, Seattle, and Chicago.

Each house is a two-story single-family building with a contemporary design. The house life cycle system-boundary includes the energy and material inputs and outputs of excavation; construction; occupancy; maintenance, repair, and replacement; demolition; and disposal. It also includes (i) the concrete upstream profile, (ii) the mass of other building materials used, (iii) occupant energy-use, and (iv) transportation energy. The partial LCI is presented in terms of energy use, material use, and emissions to air over a 100-year life.

The LCI is partial because it does not include the emissions from the production of non-cementitious building materials, such as wood, steel, and plastics. It also does not include the upstream profile of fuel and electricity production and distribution.

The results show that occupant energy-use accounts for 99% of the life cycle energy-use of the ICF house and the wood frame house. Less than 1% of the life cycle energy is due to cement manufacturing and concrete production. The house life cycle energy is primarily a function of climate and occupant behavior, not concrete content. Therefore, the ICF house, which is more energy-efficient than the wood frame house, has a lower life cycle energy-use. Furthermore, although the ICF house contains more embodied energy than the wood frame house, after 5 years in Chicago, for example, the cumulative energy use of the wood frame house surpasses that of the ICF house.

Most of the house life cycle emissions of CO_2 (97%), NO_x (83%), CO (85%), VOC (80%), and CH_4 (86%) are from the combustion of household natural gas for heating and hot water. Most of the particulate matter (60%) and SO_2 emissions (89%) are from the production of concrete.

REFERENCE

Marceau, Medgar L., Gajda, John, VanGeem, Martha G., Gentry, Thomas, and Nisbet, Michael A., "Partial Environmental Life Cycle Inventory of an Insulating Concrete Form House Compared to a Wood Frame House", PCA R&D Serial No. 2464, Portland Cement Association, Skokie, IL, September 2000, 42 pages.

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PARTIAL ENVIRONMENTAL LIFE CYCLE INVENTORY OF AN INSULATING CONCRETE FORM HOUSE COMPARED TO A WOOD FRAME HOUSE

by Medgar L. Marceau, John Gajda, Martha G. VanGeem, Thomas Gentry, and Michael A. Nisbet*

1. INTRODUCTION

The Portland Cement Association (PCA) is currently developing environmental life cycle inventory (LCI) data for use in evaluating environmental aspects of concrete products. An LCI is the compilation and quantification of energy and material inputs and outputs of a product system. The ultimate goal of this endeavor is to use the LCI data to conduct a life cycle *assessment* (LCA) of concrete products. The LCA will quantify the *impacts* of concrete products on the environment, such as climate change, acidification, nutrification, natural resource depletion, risks to human health, and other ecological consequences. An LCA can be used to compare the environmental impact of concrete products with competing construction products. The LCI data will also be available for incorporation into existing and future LCA models, which are designed to compare construction material and system alternatives and to improve construction material processes. The purpose of this report is to compare the partial LCI of a wood frame house with that of an insulating concrete form house. Further information on the target audience for this report and other project reports is presented in Appendix A.

The methodology for conducting an LCI has been documented by the United States Environmental Protection Agency,[*Life Cycle Assessment: Inventory Guidelines and Principles*, EPA/600/R-92/245, U.S. Environmental Protection Agency, Risk Reduction Engineering Laboratory, Cincinnati, OH, February 1993.] the Society of Environmental Toxicology and Chemistry (SETAC),[2] and the International Organization for Standardization (ISO).[3] The partial LCI in this report follows the guidelines proposed by SETAC. These guidelines parallel the standards proposed by ISO in ISO14040, "Environmental Management - Life Cycle Assessment - Principles and Framework," ISO 14041, "Environmental Management - Life Cycle Assessment - Goal and Scope Definition and Inventory Analysis," and other ISO documents.

The house life cycle comprises the energy and material inputs and outputs of excavation; construction; occupancy; maintenance, repair, and replacement; demolition; and disposal. The partial LCI in this report includes the upstream profile of concrete.[4] The PCA intends to include the upstream profiles of other materials (such as wood and steel) and fuels (such as coal and electricity) once a suitable database is found. Furthermore, water usage from upstream profiles and from household occupants will also be included. Figure 1-1 shows the material and energy inputs that are included in this partial LCI.

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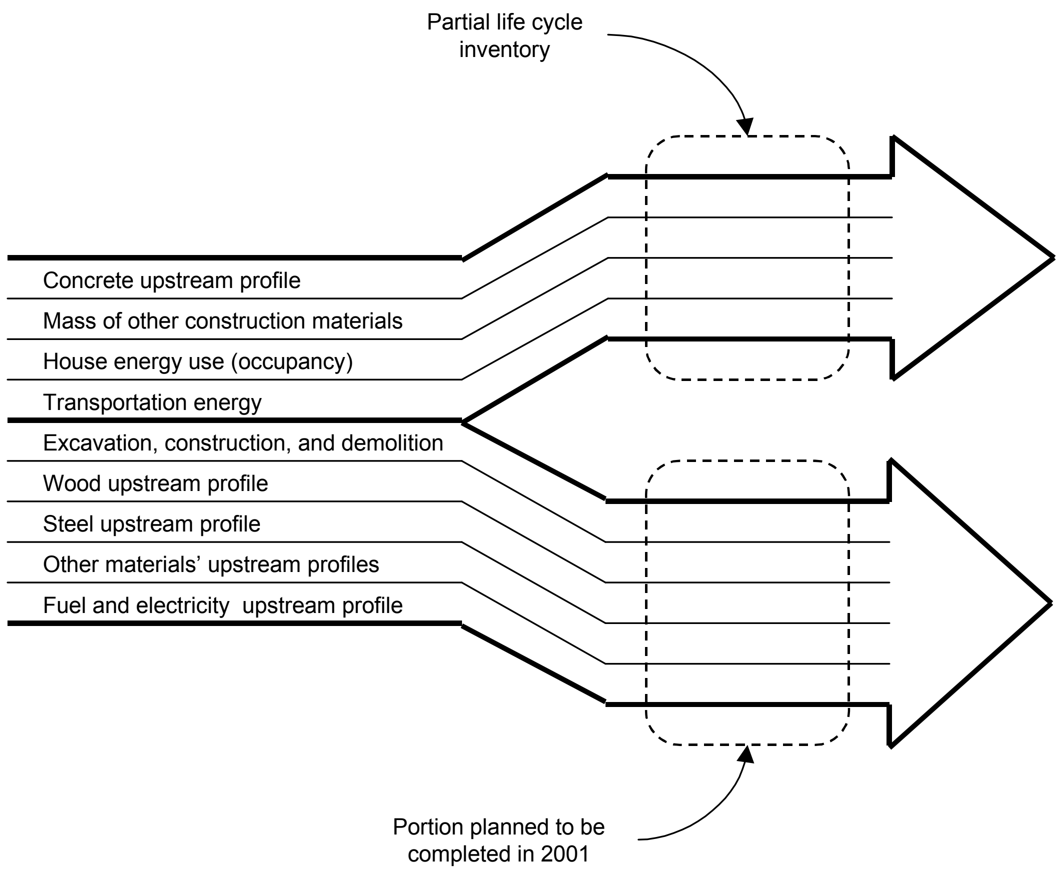

Figure 1-1. Material and energy inputs included in the partial LCI.

The partial LCI is presented in terms of energy use, material use, emissions to air, and solid waste generation; and it includes the upstream profile of concrete. The masses of other building materials used in the house are included, and they can be used as inputs in existing and future LCA models.

The same layout is used for both the wood frame house and the insulating concrete form (ICF) house. The houses are designed to meet the requirements of the 1998 International Energy Conservation Code (IECC)[5] because it is the most current and most widely used energy code in the United States. The long-term energy consumption of a building depends on local climate, so the houses are modeled in a variety of regions. Five cities were chosen that represent the range of climates in the United States: Phoenix, Miami, Washington, Seattle, and Chicago.[6] House energy consumption is modeled using Visual DOE 2.6 energy simulation software.[7]

2. SYSTEM BOUNDARY

The house life-cycle system-boundary, shown in Figure 2-1, defines the limit of the partial LCI. It includes the energy and material inputs and outputs of excavation; construction; occupancy;

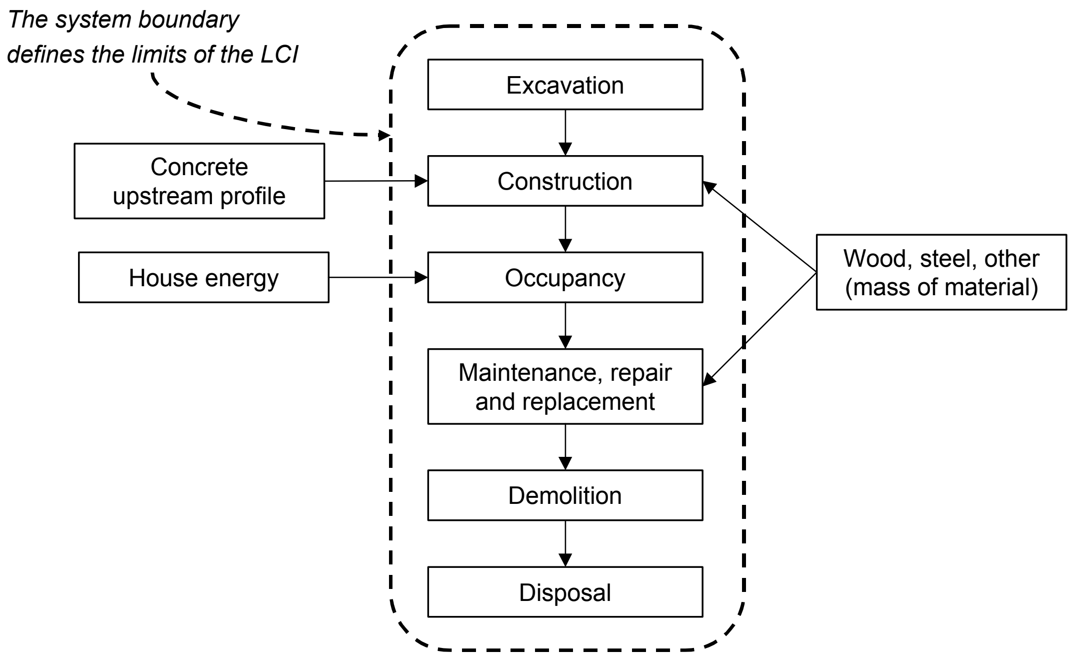

Figure 2-1. System boundary for house environmental life cycle inventory.

maintenance, repair, and replacement; demolition; and disposal. The system boundary also includes (i) the concrete upstream profile, (ii) the mass of other building materials used, (iii) occupant energy-use, and (iv) transportation energy. The transportation energy consists of the energy to transport materials from their place of origin to the house and from the house to a landfill, and the transportation energy in the upstream profiles.

The system boundary excludes human resources, the infrastructure, accidental spills, and impacts caused by personnel.

The partial LCI does not include the emissions from the production of other building materials, such as wood, steel, and plastics. It also does not include the upstream profile of fuel and electricity production and distribution.

3. HOUSE DESCRIPTION

The house described in this report was designed by Construction Technology Laboratories, Inc. (CTL), and it is based on the designs of typical houses currently being built in the United States. The house is a two-story single-family building with four bedrooms, 2.7-m (9-ft) ceilings, a two-story foyer and family room, and an attached two-car garage. The house has 228 square meters (2,450 square feet) of living space, which is somewhat larger than the 1998 U.S. average of 203 square meters (2,190 square feet).[8] The size of the house is based on the average size of ICF houses constructed in the United States.[9] Figures B1 through B8 in Appendix B present the floor plans and elevations.

The house was modeled in five cities, representing a range of U.S. climates. Phoenix was selected because it is a hot dry climate with large temperature swings where thermal mass is effective in increasing thermal comfort and in reducing energy use. Miami was selected because it is a hot humid climate with small temperature swings where thermal mass works almost as well. Washington and Seattle were selected because they are moderate climates. Chicago was selected because it is a cold climate.

The building envelope in each location was designed to meet the minimum requirements of the 1998 IECC using standard building materials.[5] The IECC minimum requirements for thermal resistance are presented in Table 3-1 for each of the five cities where the house is modeled. R-value refers to thermal resistance in m^2·K/W (hr·ft^2·°F/Btu) and U-factor refers to heat flow per unit area in W/m^2·K (Btu/hr·ft^2·°F). The maximum U-factor is equivalent to the inverse of the minimum R-value. Variations in regional building materials and practices, such as the use of crawl spaces and basements, are not considered in order to simplify the analyses and in order to compare energy use across all cities.

In all cities, the house is slab-on-grade construction. The slab-on-grade floor consists of carpeted 150-mm (6-in.) thick normal-weight concrete cast on soil. The U-factor of the floor is 1.53 W/m^2·K (0.27 Btu/hr·ft^2·°F). Although the IECC requires perimeter insulation for slabs-on-grade in most areas of the United States, commonly used and accepted energy modeling software cannot model perimeter insulation. Therefore, the slab-on-grade is uninsulated. Second story floors are carpeted wood-framed assemblies without insulation.

The exterior walls of the wood frame house consist of medium-colored aluminum siding, 12-mm (½-in.) plywood, R_{SI}-1.9 (R-11) fiberglass batt insulation, and 12-mm (½-in.) painted gypsum board. The exterior walls of the ICF house consists of medium-colored aluminum siding; flat panel ICF system with 50 mm (2 in.) expanded polystyrene insulation, 150 mm (6 in.) normal weight concrete, and 50 mm (2 in.) expanded polystyrene insulation with plastic ties; and 12-mm (½-in.) painted gypsum board. Figures B7 and B8 in Appendix B show the wall cross-sections. For both house styles, all exterior garage walls (except the front wall of the garage, which has overhead doors) and the common wall between house and garage are of the same construction as the exterior walls of the house. The front wall of the garage is modeled as a low-mass light-colored wall with a U-factor of 2.8 W/m^2·K (0.50 Btu/hr·ft^2·°F). Interior walls are wood frame construction and uninsulated.

Roofs are wood frame construction with R_{SI}-3.3, R_{SI}-5.3, or R_{SI}-6.7 (R-19, R-30, or R-38) fiberglass batt insulation. They are covered with medium-colored asphalt shingles.

Windows are primarily located on the front and back façades, and the overall window-to-exterior wall ratio is 16%. The windows were chosen to meet the IECC requirements for solar heat gain coefficient (SHGC) and U-factor. They consist of double pane glass with a low-E coating. To meet the SHGC requirement, windows in Miami and Phoenix are tinted and contain air in the space between panes. Windows in Seattle, Chicago, and Washington are not tinted and contain argon gas in the space between panes. Interior shades or drapes are assumed to be closed during periods of high solar heat gains. The houses are assumed to be located in new developments without trees or any other form of exterior shading.

Table 3-2 presents the assembly U-factors used in the analyses. In most cases, using typical building materials results in assemblies that exceed the IECC U-factor requirements.

Table 3-1. International Energy Conservation Code Maximum U-factors*

Location	Opaque walls**				Roof		Windows***	
	Wood frame		Mass					
	$\frac{W}{m^2 \cdot K}$	$\frac{Btu}{hr \cdot ft^2 \cdot {}^\circ F}$	$\frac{W}{m^2 \cdot K}$	$\frac{Btu}{hr \cdot ft^2 \cdot {}^\circ F}$	$\frac{W}{m^2 \cdot K}$	$\frac{Btu}{hr \cdot ft^2 \cdot {}^\circ F}$	$\frac{W}{m^2 \cdot K}$	$\frac{Btu}{hr \cdot ft^2 \cdot {}^\circ F}$
Miami	0.937	0.165	1.164	0.205	0.278	0.049	4.2	0.74
Phoenix	0.960	0.169	1.187	0.209	0.238	0.042	2.4	0.47
Seattle	0.653	0.115	0.750	0.132	0.187	0.033	1.7	0.30
Washington	0.642	0.113	0.732	0.129	0.182	0.032	1.7	0.30
Chicago	0.466	0.082	0.466	0.082	0.148	0.026	1.6	0.28

* The maximum U-factor is equal to the inverse of the minimum R-value.
** Calculated based on the house design and the window U-factors prescribed by the IECC.
*** The code also requires that windows have a solar heat gain coefficient (SHGC) less than 0.4 in Miami and Phoenix.

Table 3-2. Assembly U-Factors*

<table>
<tr><th rowspan="3">Location</th><th colspan="4">Walls</th><th colspan="2" rowspan="2">Roof**</th><th colspan="2" rowspan="2">Windows</th></tr>
<tr><th colspan="2">Wood frame</th><th colspan="2">Mass (ICF)</th></tr>
<tr><th>$\frac{W}{m^2 \cdot K}$</th><th>$\frac{Btu}{hr \cdot ft^2 \cdot {}^\circ F}$</th><th>$\frac{W}{m^2 \cdot K}$</th><th>$\frac{Btu}{hr \cdot ft^2 \cdot {}^\circ F}$</th><th>$\frac{W}{m^2 \cdot K}$</th><th>$\frac{Btu}{hr \cdot ft^2 \cdot {}^\circ F}$</th><th>$\frac{W}{m^2 \cdot K}$</th><th>$\frac{Btu}{hr \cdot ft^2 \cdot {}^\circ F}$</th></tr>
<tr><td>Miami</td><td rowspan="5">0.47</td><td rowspan="5">0.082</td><td rowspan="5">0.31</td><td rowspan="5">0.055</td><td>0.27</td><td>0.048</td><td rowspan="2">2.4</td><td rowspan="2">0.43</td></tr>
<tr><td>Phoenix</td><td rowspan="3">0.18</td><td rowspan="3">0.032</td></tr>
<tr><td>Seattle</td><td rowspan="3">1.5</td><td rowspan="3">0.27</td></tr>
<tr><td>Washington</td></tr>
<tr><td>Chicago</td><td>0.15</td><td>0.026</td></tr>
</table>

* The maximum U-factor is equal to the inverse of the minimum R-value.
** R_{SI}-3.3 (R-19) attic insulation was used in Miami, R_{SI}-6.7 (R-38) attic insulation was used in Chicago, and R_{SI}-5.3 (R-30) attic insulation was used in the remaining cities.

4. ASSUMPTIONS

In order to create a realistic house model, the following assumptions about occupant behavior and house performance have been made. These assumptions also ensure that comparisons between house styles are possible.

Hot water is supplied by a natural gas water heater, which has a peak utilization of 24 liters/minute (2.5 gallons/minute). The hot water load-profile was taken from ASHRAE Standard 90.2.[10] The heating, ventilating, and air-conditioning (HVAC) system consists of a natural gas high-efficiency forced-air system with a high-efficiency central air conditioner. The efficiencies of the HVAC system components are assumed to be identical in all cities.

The HVAC system is controlled by a residential set-back thermostat located in the family room. The cooling set-point temperature is 24°C (75°F) from 6 AM to 10 PM and 26°C (78°F) from 10 PM to 6 AM. The heating set-point temperature is 21°C (70°F) from 6 AM to 10 PM and 18°C (65°F) from 10 PM to 6 AM.

Occupant energy consumption for uses other than heating and cooling is assumed to be 23.36 kWh/day. This value was calculated from ASHRAE Standard 90.2,[10] and it assumes the house has an electric clothes dryer and an electric stove.

Air infiltration rates are based on ASHRAE Standard 62.[11] The air infiltration rate is 0.35 air changes per hour (ACH) in the living areas of the house and 2.5 ACH in the unconditioned attached garage. A family of four is assumed to live in the house.

The life of the house is assumed to be 100 years. The maintenance, repair, and replacement schedules for various building components are shown in Table 4-1.

5. INVENTORY ANALYSIS

The partial life cycle inventory of the house comprises the energy and material inputs and outputs of all the activities included in the system boundary shown in Figure 2-1. These activities are excavation; construction; occupancy; maintenance, repair, and replacement; demolition; and disposal. The partial LCI in this report includes the upstream profile of concrete.[4] The PCA intends to include the upstream profiles of other materials once a suitable database is found.

The SETAC guidelines[2] indicate that inputs to a process do not need to be included in an LCI if (i) they are less than 1% of the total mass of the processed materials or product, (ii) they do not contribute significantly to a toxic emission, and (iii) they do not have a significant associated energy consumption.

5.1. Material inputs

The material inputs to the partial LCI are made up of the material inputs to construction, maintenance, repair, and replacement.

5.1.1. House material inputs

The material inputs to construction, maintenance, repair, and replacement are calculated from the house plans and elevations and from the house component replacement schedule. Table 5-1 shows a summary of the material inputs over the 100-year life of the house in each city. A detailed material list is shown in Table C-1 in Appendix C.

Both houses contain similar amounts of wood because in both houses the roof, the interior walls, the second story floor, and the windows and doors are framed with wood. There is more gypsum wallboard in the ICF house because the exposed ICF surfaces in the garage are sheathed with gypsum (a flame retardant materials) for reasons of fire safety.

Table 4-1. House Component Replacement Schedules

House component	Replacement schedule (years)
Siding, air barrier, and exterior fixtures	33.3
Latex and silicone caulking	10
Paint, exterior	5
Doors and windows	33.3
Roofing*	20 and 40
Gable and ridge vents	33.3
Bathroom fixtures	25
Bathroom tiles and backer board	25
Paint, interior	10
Carpet and pad	10
Resilient flooring, vinyl sheet	10
Bathroom furniture (toilet, sink, etc.)	25
Garbage disposal	20
Furnace	20
Air conditioner	20
Interior and exterior luminaries	33.3
Water heater	20
Large appliances	15
Manufactured fireplace	50
Kitchen and bathroom casework	25
Kitchen counter tops	25

* A new layer of shingles is added every 20 years, and every 40 years the existing layers of felt and shingles are replaced with a new layer of felt and shingles.

The material inputs also include packaging. Almost all material delivered to the site is packaged in some way. The item labeled *shipping weight* in Table 5-1 includes the packaging for large items like appliances, and Table C-2 in Appendix C lists the items that contribute to shipping weight. The amount of packaging for concrete, wood, steel, and board stock is minimal so it is ignored. Wood pallets are reused and do not contribute to the waste stream. The amount of packaging for all other materials not listed in Table C-2 can be quite substantial in volume; however, on a mass basis it is less than 1% of the material packaged, so it is ignored. Construction waste is included in the mass of material listed in Table 5-1.

5.1.2. Concrete upstream profile

Table 5-2 shows the material inputs to the concrete portion of the house in each city. The concrete material upstream profile is based on the upstream profile for a 21 MPa (3,000 psi) concrete mix. The mix proportions are presented in Table 5-3. Concrete mix proportions vary depending on available materials and suppliers. More information on the effects of concrete mix proportions on LCI results is given in Reference 4. Data are generally U.S. industry averages where available. The ICF house has about twice as much concrete as the wood frame house

Table 5-1A. House Materials List – SI Units*

	Wood frame house					ICF house				
Material, kg	**Miami**	**Phoenix**	**Seattle**	**DC**	**Chicago**	**Miami**	**Phoenix**	**Seattle**	**DC**	**Chicago**
Ready-mixed concrete**	70,700	76,200	76,200	87,200	109,200	193,700	199,200	199,200	210,200	232,300
Fiber-cement backer board	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500
Metal**	3,500	3,500	3,500	3,700	3,900	5,000	5,100	5,100	5,200	5,500
Wood	20,400	20,400	20,400	20,400	20,400	17,200	17,200	17,200	17,200	17,200
Gypsum wallboard	8,900	8,900	8,900	8,900	8,900	9,700	9,700	9,700	9,700	9,700
Insulation, polystyrene**	0	30	30	90	210	1,920	1,950	1,950	2,010	2,130
Insulation, fiberglass	430	540	540	540	630	210	330	330	330	410
Polymers, various	10,200	10,200	10,200	10,200	10,200	10,100	10,100	10,100	10,100	10,100
Roofing materials	5,800	5,800	5,800	5,800	5,800	5,800	5,800	5,800	5,800	5,800
Windows	3,100	3,100	3,100	3,100	3,100	3,100	3,100	3,100	3,100	3,100
Tile	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600
Lighting products	600	600	600	600	600	600	600	600	600	600
Electrical wire	110	110	110	110	110	110	110	110	110	110
Shipping weight, various***	5,500	5,500	5,500	5,500	5,500	5,500	5,500	5,500	5,500	5,500
Total materials, kg	**134,400**	**140,100**	**140,100**	**151,300**	**173,800**	**258,100**	**263,800**	**263,800**	**275,000**	**297,600**

*Includes items replaced during the 100-year life.
**More material is used in colder climates because foundations are deeper.
***See Table C-2 in Appendix C for a listing of other items that contribute to shipping weight.

Table 5-1B. House Materials List – U.S. Customary Units*

	Wood frame house					ICF house				
Material, lb	**Miami**	**Phoenix**	**Seattle**	**DC**	**Chicago**	**Miami**	**Phoenix**	**Seattle**	**DC**	**Chicago**
Ready-mixed concrete**	155,800	167,900	167,900	192,200	240,700	427,100	439,200	439,200	463,500	512,100
Fiber-cement backer board	3,400	3,400	3,400	3,400	3,400	3,400	3,400	3,400	3,400	3,400
Metal**	7,600	7,800	7,800	8,100	8,700	11,100	11,200	11,200	11,500	12,200
Wood	45,000	45,000	45,000	45,000	45,000	37,900	37,900	37,900	37,900	37,900
Gypsum wallboard	19,600	19,600	19,600	19,600	19,600	21,300	21,300	21,300	21,300	21,300
Insulation, polystyrene**	0	70	70	200	460	4,240	4,300	4,300	4,440	4,700
Insulation, fiberglass	950	1,200	1,200	1,200	1,380	470	720	720	720	900
Polymers, various	22,600	22,600	22,600	22,600	22,600	22,200	22,200	22,200	22,200	22,200
Roofing materials	12,800	12,800	12,800	12,800	12,800	12,800	12,800	12,800	12,800	12,800
Windows	6,900	6,900	6,900	6,900	6,900	6,900	6,900	6,900	6,900	6,900
Tile	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000
Lighting products	1,300	1,300	1,300	1,300	1,300	1,300	1,300	1,300	1,300	1,300
Electrical wire	250	250	250	250	250	250	250	250	250	250
Shipping weight, various***	12,100	12,100	12,100	12,100	12,100	12,100	12,100	12,100	12,100	12,100
Total materials, lb	**296,300**	**308,900**	**308,900**	**333,600**	**383,200**	**569,000**	**581,700**	**581,700**	**606,400**	**656,000**

*Includes items replaced during the 100-year life.
**More material is used in colder climates because foundations are deeper.
***See Table C-2 in Appendix C for a listing of other items that contribute to shipping weight.

Table 5-2A. Concrete Material Input from Concrete Upstream Profile – SI Units

	Wood frame house					ICF house				
Material, kg	**Miami**	**Phoenix**	**Seattle**	**DC**	**Chicago**	**Miami**	**Phoenix**	**Seattle**	**DC**	**Chicago**
Cement	6,800	7,300	7,300	8,400	10,500	18,600	19,100	19,100	20,200	22,300
Water	4,300	4,600	4,600	5,300	6,600	11,700	12,100	12,100	12,700	14,100
Coarse aggregate	34,300	37,000	37,000	42,300	53,000	94,100	96,700	96,700	102,100	112,800
Fine aggregate	25,300	27,300	27,300	31,200	39,100	69,300	71,300	71,300	75,200	83,100
Concrete (total)	**70,700**	**76,200**	**76,200**	**87,200**	**109,200**	**193,700**	**199,200**	**199,200**	**210,200**	**232,300**

Table 5-2B. Concrete Material Input from Concrete Upstream Profile – U.S. Customary Units

	Wood frame house					ICF house				
Material, lb	**Miami**	**Phoenix**	**Seattle**	**DC**	**Chicago**	**Miami**	**Phoenix**	**Seattle**	**DC**	**Chicago**
Cement	15,000	16,100	16,100	18,500	23,100	41,000	42,200	42,200	44,500	49,200
Water	9,400	10,200	10,200	11,600	14,600	25,900	26,600	26,600	28,100	31,000
Coarse aggregate	75,600	81,500	81,500	93,300	116,900	207,400	213,300	213,300	225,100	248,600
Fine aggregate	55,700	60,100	60,100	68,800	86,100	152,800	157,100	157,100	165,800	183,200
Concrete (total)	**155,800**	**167,900**	**167,900**	**192,200**	**240,700**	**427,100**	**439,200**	**439,200**	**463,500**	**512,100**

Table 5-3. Mix Design for 21 MPa (3,000 psi) Concrete*

Material, lb	**Lake Charles**	**Tucson**
Ready-mixed concrete		
Cement	14,969	16,135
Water	9,435	10,170
Coarse aggregate	75,641	81,534
Fine aggregate	55,735	60,078

*Concrete mix designs vary. This one has been chosen because it is representative of residential concrete.

because, in addition to the foundation, the exterior walls are also concrete. The houses in the cooler climates also have more concrete because they have deeper concrete foundations.

5.2. Energy inputs

The energy inputs to the partial LCI are made up of the energy inputs to excavation, construction, maintenance, occupancy, demolition, and disposal. The partial LCI also includes energy used to produce concrete. This is the embodied energy of concrete and it is part of the concrete upstream profile.

5.2.1. Excavation and construction

Most of the energy used in excavation and construction is for transporting materials from their place of origin to the house construction site. Energy used on site by excavation and construction equipment is assumed to be less than 1% of the life cycle energy so it is not included in the LCI. All material is assumed to be transported by tractor-trailers using diesel fuel and traveling on paved roads. The average haul distance is assumed to be 80 kilometers (50 miles) for all material. The energy consumption of 1,060 joules per kilogram-kilometer (1,465 Btu per ton-mile) is based on the assumption that transportation energy efficiency is 24 liters of diesel fuel per 1,000 metric ton-kilometers (9.4 gallons of diesel fuel per 1,000 ton-miles).[12] Table 5-4 shows the transportation energy used to transport materials to the construction site. This partial LCI does not consider the energy used in return trips when the tractor-trailer is empty because this type of vehicles usually makes deliveries at several job sites per trip. Therefore, the assumptions about transportation energy consumption are conservative.

5.2.2. Concrete embodied energy

Table 5-4 also shows the embodied energy of the concrete portion of the house in each city. The concrete embodied energy includes energy and emissions form the transportation of primary materials from their source to the cement and concrete plants, and from operations at the cement and concrete plants. It does not include upstream profiles of fuels or electricity. The concrete embodied energy of the house is directly related to the amount of concrete used in the house. Although cement makes up less than 10% by weight of concrete, about 70% of the energy embodied in concrete is consumed in the cement manufacturing process.[4]

5.2.3. Household occupant energy-use

Visual DOE 2.6 energy simulation software is used to model the annual household energy consumption.[5] This software uses the United States Department of Energy DOE 2.1-E hourly simulation tool as the calculation engine. It is used to simulate hourly energy use and peak demand over a one-year period. Because heating and cooling load vary with solar orientation, the house is modeled four times: once for each orientation of the façade facing the four cardinal points (north, south, east, and west). Then the total energy consumption for heating, cooling, hot water, and occupant use is averaged to produce a building-orientation-independent energy consumption. The annual occupant energy-use is presented in Table 5-5. Results for the 100-year life are presented in Table 5-4.

Table 5-4A. 100-Year Life Cycle Energy Use – SI Units*

	Wood frame house					ICF house				
	Miami	Phoenix	Seattle	DC	Chicago	Miami	Phoenix	Seattle	DC	Chicago
Diesel fuel, L**										
Transportation to house	264	275	275	297	341	506	517	517	539	584
Transportation to landfill	264	275	275	297	341	506	517	517	539	584
Energy, GJ										
Transportation to house	10	11	11	11	13	20	20	20	21	23
Embodied in concrete	52	56	56	64	80	142	146	146	154	171
Occupant use	10,640	14,510	22,000	21,370	25,600	10,070	13,380	20,030	19,710	23,530
Transportation to landfill	10	11	11	11	13	20	20	20	21	23
Total	**10,712**	**14,588**	**22,078**	**21,456**	**25,706**	**10,252**	**13,566**	**20,216**	**19,906**	**23,746**

*Does not include upstream profile of electricity, fuel, or materials other than concrete.
**Heating value of diesel fuel: 0.038 GJ/L.

Table 5-4B. 100-Year Life Cycle Energy Use – U.S. Customary Units*

	Wood frame house					ICF house				
	Miami	Phoenix	Seattle	DC	Chicago	Miami	Phoenix	Seattle	DC	Chicago
Diesel fuel, gallon**										
Transportation to house	70	73	73	78	90	134	137	137	142	154
Transportation to landfill	70	73	73	78	90	134	137	137	142	154
Energy, MBtu										
Transportation to house	10	10	10	11	12	19	19	19	20	21
Embodied in concrete	49	53	53	61	76	135	139	139	146	162
Occupant use	10,077	13,742	20,836	20,239	24,245	9,537	12,672	18,970	18,667	22,285
Transportation to landfill	10	10	10	11	12	19	19	19	20	21
Total	**10,146**	**13,815**	**20,909**	**20,322**	**24,346**	**9,709**	**12,849**	**19,147**	**18,853**	**22,489**

*Does not include upstream profile of electricity, fuel, or materials other than concrete.
**Heating value of diesel fuel: 0.138 MBtu/gallon.

Table 5-5. Annual Occupant Energy-Use by Location

Location	Variation	Annual operating data				
		Electricity		Natural gas		Total energy, GJ
		GJ	kWh	GJ	therms	
Miami	Wood frame	65.3	18,130	41.1	390	106.4
	ICF	61.1	16,980	39.6	380	100.7
Phoenix	Wood frame	75.6	21,000	69.5	670	145.1
	ICF	70.2	19,500	63.6	600	133.8
Seattle	Wood frame	35.4	9,840	184.6	1,750	220.0
	ICF	34.6	9,600	165.7	1,570	200.3
Washington	Wood frame	43.4	12,060	170.2	1,610	213.7
	ICF	41.5	11,520	155.7	1,480	197.1
Chicago	Wood frame	41.5	11,540	214.4	2,030	256.0
	ICF	39.8	11,060	195.5	1,850	235.3

The data presented in Table 5-5 show that, in each of the five climates, the ICF house has lower occupant energy use than the wood frame house. In the simulations, the ICF house was modeled with a standard ICF wall configuration while the wood frame house was modeled with standard materials needed to meet IECC requirements. In all cases but one (the wood frame house in Chicago), the R-values of ICF and wood frame walls significantly exceed IECC requirements. Wood frame walls have R-values that range from 0 to 105% in excess of IECC requirements, while ICF walls have R-values that range from 50 to 210% in excess of IECC requirements.

Another important difference between the two houses is that the energy required for heating, ventilating, and air-conditioning is less for the ICF house than for the wood frame house. Table 5-6 shows the HVAC system requirements as determined by the energy simulation software. The thermal mass of the ICF house moderates temperature swings and peak loads, and results in lower HVAC system requirements. The large capacity required in Phoenix is due to the large daily temperature swings in that city.

Natural gas fired high-efficiency forced-air furnaces are typically available in 20 kBtu/hr capacity increments (equivalent to 5.9 kW) and high-efficiency central air conditioners are typically available in 6 to 12 kBtu/hr (½ to 1 ton) capacity increments (equivalent to 1.8 to 3.5 kW). Because HVAC systems are typically oversized (the installed capacity is the required capacity rounded to the next larger available capacity), actual installed system capacity savings will be different.

5.2.4. Maintenance, repair, and replacement

The materials used for maintenance, repair, and replacement are included in the house materials list in Table C-1, Appendix C. Most of the energy used in maintenance, repair, and replacement is used to transport materials from their place of origin to the house. This transportation energy is included in the transportation values in Table 5-4.

Table 5-6. Required HVAC System Capacity as Determined by Energy Simulation Software

Location	Variation	System capacity			
		Heating		Cooling	
		kW	kBtu/hr	kW	kBtu/hr
Miami	Wood frame	25	87	13	44
	ICF	21	73	11	37
Phoenix	Wood frame	35	119	21	70
	ICF	30	103	18	61
Seattle	Wood frame	26	90	14	46
	ICF	21	71	11	36
Washington	Wood frame	27	93	14	48
	ICF	23	79	12	41
Chicago	Wood frame	26	90	14	46
	ICF	22	76	12	39

5.2.5. Demolition and disposal

The energy used in demolition and disposal is similar to that used in excavation and construction. The energy used to demolish the house is assumed to be less than 1% of the life-cycle energy and is therefore not included in the LCI. Most of the energy is used to transport materials from the house to the landfill. All material is assumed to be transported by tractor-trailers using diesel fuel and traveling on paved roads. The average haul distance is assumed to be 80 kilometers (50 miles) for all material. The energy consumption of 1,060 joules per kilogram-kilometer (1,465 Btu per ton-mile) assumes that transportation energy efficiency is 24 liters of diesel fuel per 1,000 metric ton-kilometers (9.4 gallons of diesel fuel per 1,000 ton-miles).[12] Disposal energy is listed as transportation to landfill in Table 5-4. This LCI does not consider energy used in return trips when the tractor-trailer is empty.

5.2.6. Total energy inputs

Table 5-7 shows a summary of the life cycle energy of each house. This partial LCI includes the embodied energy of concrete but not the embodied energy of other building materials, such as wood, steel, and plastic. These upstream profiles will be added to the LCI once a suitable database is found. Table D-1 in Appendix D shows in more detail the life cycle fuel and electricity use.

Table 5-7 shows that occupant energy-use is 99% of life cycle energy-use. This means that the house life cycle energy is not sensitive to variations in cement manufacturing, concrete production, nor transportation. The house life cycle energy is primarily a function of climate and occupant behavior, not concrete content. Therefore, the ICF house, which is more energy-efficient than the wood frame house, has a lower life cycle energy-use. Figure 5-1 shows the life cycle energy-use profile of the wood frame house and the ICF house in Chicago. It shows that after 5 years, the cumulative energy use of the wood frame house exceeds that of the ICF house.

Table 5-7A. Energy Summary for 100-Year Life Cycle – SI Units*

	Wood frame house					ICF house				
	Miami	**Phoenix**	**Seattle**	**DC**	**Chicago**	**Miami**	**Phoenix**	**Seattle**	**DC**	**Chicago**
Energy, GJ										
Transportation to house	10	11	11	11	13	20	20	20	21	23
Embodied in concrete	52	56	56	64	80	142	146	146	154	171
Occupant use	10,640	14,510	22,000	21,370	25,600	10,070	13,380	20,030	19,710	23,530
Transportation to landfill	10	11	11	11	13	20	20	20	21	23
Total	**10,712**	**14,588**	**22,078**	**21,456**	**25,706**	**10,252**	**13,566**	**20,216**	**19,906**	**23,746**
Percent of total energy use, %										
Transportation to house	0.1	0.1	0.0	0.1	0.1	0.2	0.1	0.1	0.1	0.1
Embodied in concrete	0.5	0.4	0.3	0.3	0.3	1.4	1.1	0.7	0.8	0.7
Occupant use	99.3	99.5	99.6	99.6	99.6	98.2	98.6	99.1	99.0	99.1
Transportation to landfill	0.1	0.1	0.0	0.1	0.1	0.2	0.1	0.1	0.1	0.1

*Does not include upstream profile of electricity, fuel, or materials other than concrete.

Table 5-7B. Energy Summary for 100-Year Life Cycle – U.S. Customary Units*

	Wood frame house					ICF house				
	Miami	**Phoenix**	**Seattle**	**DC**	**Chicago**	**Miami**	**Phoenix**	**Seattle**	**DC**	**Chicago**
Energy, MBtu										
Transportation to house	10	10	10	11	12	19	19	19	20	21
Embodied in concrete	49	53	53	61	76	135	139	139	146	162
Occupant use	10,085	13,753	20,852	20,255	24,264	9,545	12,682	18,985	18,681	22,302
Transportation to landfill	10	10	10	11	12	19	19	19	20	21
Total	**10,154**	**13,826**	**20,925**	**20,338**	**24,365**	**9,716**	**12,858**	**19,161**	**18,867**	**22,506**
Percent of total energy use, %										
Transportation to house	0.1	0.1	0.0	0.1	0.1	0.2	0.1	0.1	0.1	0.1
Embodied in concrete	0.5	0.4	0.3	0.3	0.3	1.4	1.1	0.7	0.8	0.7
Occupant use	99.3	99.5	99.7	99.6	99.6	98.2	98.6	99.1	99.0	99.1
Transportation to landfill	0.1	0.1	0.0	0.1	0.1	0.2	0.1	0.1	0.1	0.1

*Does not include upstream profile of electricity, fuel, or materials other than concrete.

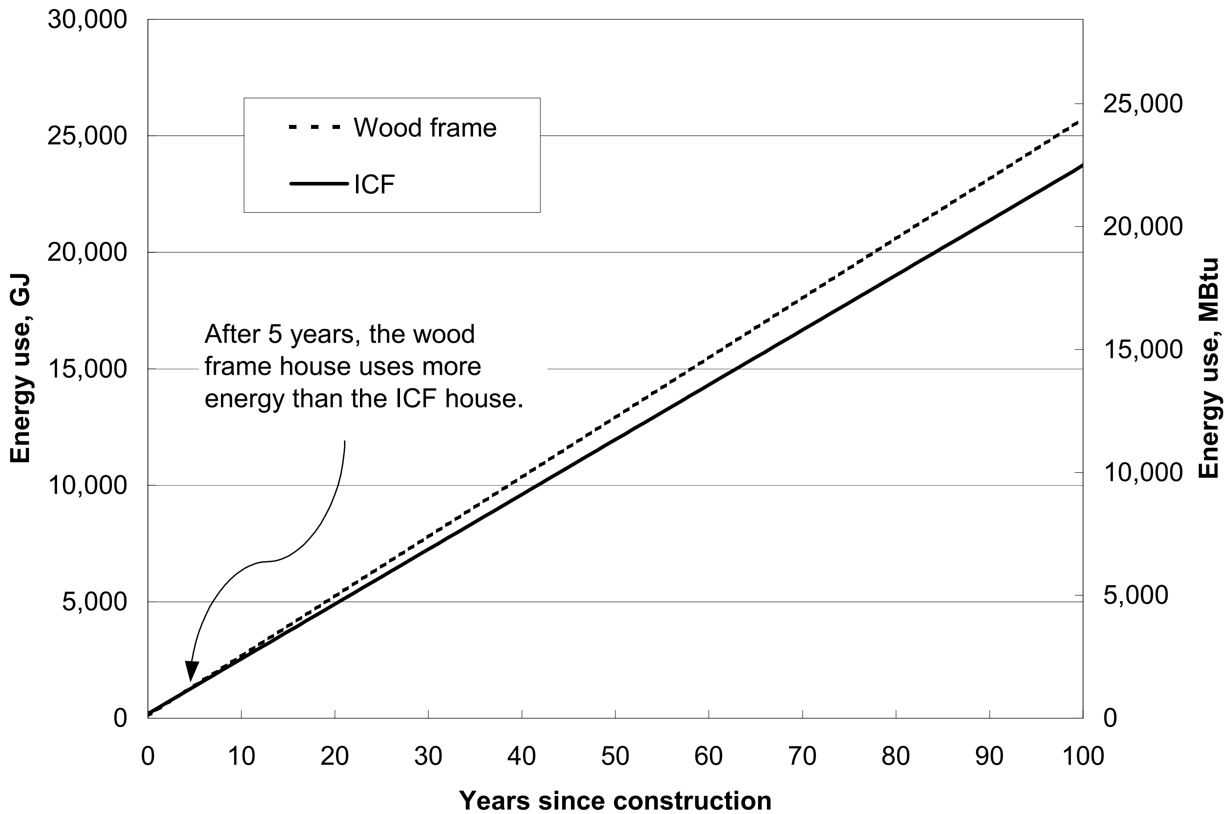

Figure 5-1. Cumulative life cycle energy use of wood frame house and ICF house in Chicago over 100 years. (Does not include upstream profiles of electricity, fuel, or construction materials other than concrete.)

5.3. Material outputs

The life cycle material outputs from the house are made up of the material outputs from excavation; construction; occupancy; maintenance, repair, and replacement; demolition; and disposal. The material outputs are emissions to air and solid waste. The PCA intends to include the upstream profiles of other materials, such as wood and steel; and fuels, such as coal and electricity, once a suitable database is found. Furthermore, water usage from upstream profiles and from household occupants will also be included.

5.3.1. Emissions to air

This partial LCI includes emissions to air of greenhouse gases and the most common air pollutants as defined by United Sates Environmental Protection Agency.[13] These emissions consist of particulate matter from point and fugitive sources and the following combustion gases: carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOC), and methane (CH_4). Hazardous air pollutants, such as hydrogen chloride, mercury, dioxins, and furans, are excluded from the house LCI because there is insufficient information to accurately quantify their emission from the manufacture of cement.

Most of the life cycle emissions to air for the houses are from the two natural gas burning appliances (furnace and water heater). Table 5-8 shows the emissions associated with the manufacture of the concrete portion of the house, and Table 5-9 shows the emissions from the operation of the natural gas appliances. Table 5-10 shows the emissions from transportation of materials from their place of origin to the house site and from the house site to the landfill for disposal. Table 5-11 shows the total life cycle emissions of each house from cement manufacturing, concrete production, the two natural gas burning appliances (furnace and water heater), and material transportation. This LCI does not include the emissions from the manufacture of other building materials, such as wood, steel, and plastic. Nor does it include the upstream profiles for fuels. These upstream profiles will be added to the LCI once a suitable database is found.

The concrete portion of an ICF house represents about 70% of the total particulate matter released to the air, and the concrete portion of a wood frame house represents approximately 50% of the total particulate matter released to the air.

The manufacture of the concrete portion of the ICF house accounts for 2 to 9% of the total CO_2 emissions throughout the life of the house, and the manufacture of the concrete portion of the wood frame house accounts for 1 to 3% of the total CO_2 emissions throughout the life of the house. The manufacture of the concrete portion of the ICF house accounts for approximately 92% of the total SO_2 emissions, and the manufacture of the concrete portion of the wood frame house accounts for approximately 86% of the total SO_2 emissions.

Approximately 95% of the CO_2 emissions are from the combustion of natural gas appliances in the ICF house, and approximately 98% of the CO_2 emissions are from the combustion of natural gas appliances in the wood frame house. Approximately 78% of the NO_x emissions are from the combustion of natural gas appliances in the ICF house, and approximately 89% of the NO_x emissions are from the combustion of natural gas appliances in the wood frame house. In both houses, natural gas appliances contribute an average of 80 to 90% of the emissions of CO and CH_4. Approximately 75% of the VOC emissions are from the combustion of natural gas appliances in the ICF house, and 85% of the VOC emissions are from the combustion of natural gas appliances in the wood frame house.

5.3.2. Solid waste

At the end of the 100-year life, the house materials and components can be reused and recycled. However, there is little information on how much building material is reused and recycled from the demolition of a building.[15, 16] So, until reliable data are available, all house materials are assumed to be disposed of in a landfill.

5.4. Energy output

The life cycle energy output from the house is made up of the energy outputs from occupancy; maintenance, repair and replacement; and demolition. The energy output is primarily in the form of waste heat. Waste heat associated with cement manufacturing is 1.39 megajoules per kilogram of cement (1.19 million Btu per ton of cement)[17]. This is heat lost primarily in exhaust gases from the kiln and cooler and also heat loss by radiation from the kiln shell and other hot surfaces.

Table 5-8A. Emissions from Concrete Upstream Profile – SI Units

	Wood frame house					ICF house				
Emission, kg	**Miami**	**Phoenix**	**Seattle**	**DC**	**Chicago**	**Miami**	**Phoenix**	**Seattle**	**DC**	**Chicago**
Ready-mixed concrete										
Particulate matter	33	35	35	40	50	89	92	92	97	107
CO_2	6,890	7,420	7,420	8,500	10,640	18,880	19,420	19,420	20,490	22,640
SO_2	30	32	32	37	46	81	84	84	88	98
NO_x	28	31	31	35	44	78	80	80	84	93
VOC	1	1	1	1	2	3	3	3	3	4
CO	4	5	5	6	7	12	13	13	13	15
CH_4	0	1	1	1	1	1	1	1	1	2

Table 5-8B. Emissions from Concrete Upstream Profile – U.S. Customary Units

	Wood frame house					ICF house				
Emission, lb	**Miami**	**Phoenix**	**Seattle**	**DC**	**Chicago**	**Miami**	**Phoenix**	**Seattle**	**DC**	**Chicago**
Ready-mixed concrete										
Particulate matter	72	77	77	89	111	197	202	202	214	236
CO_2	15,190	16,370	16,370	18,730	23,470	41,630	42,820	42,820	45,180	49,910
SO_2	65	71	71	81	101	179	184	184	195	215
NO_x	63	67	67	77	97	172	176	176	186	206
VOC	2	3	3	3	4	7	7	7	7	8
CO	10	11	11	12	15	27	28	28	29	33
CH_4	1	1	1	1	2	3	3	3	3	4

Table 5-9A. Combustion Emissions from Occupant Use of Natural Gas – SI Units

	Wood frame house					ICF house				
	Miami	Phoenix	Seattle	DC	Chicago	Miami	Phoenix	Seattle	DC	Chicago
Natural gas, GJ:	4,110	6,950	18,460	17,020	21,440	3,960	6,360	16,570	15,570	19,550
Emission, kg										
Particulate matter	13	22	59	54	69	13	20	53	50	63
CO_2	208,000	351,000	933,000	860,000	1,084,000	200,000	321,000	837,000	787,000	988,000
SO_2	1	2	5	4	5	1	2	4	4	5
NO_x	163	275	731	674	849	157	252	656	616	774
VOC	10	16	43	39	50	9	15	38	36	45
CO	69	117	311	287	361	67	107	279	262	329
CH_4	4	7	18	16	21	4	6	16	15	19

*Natural gas burned in furnace and water heater.
Source: Reference 14.

Table 5-9B. Combustion Emissions from Occupant Use of Natural Gas – U.S. Customary Units

	Wood frame house					ICF house				
	Miami	Phoenix	Seattle	DC	Chicago	Miami	Phoenix	Seattle	DC	Chicago
Natural gas*, therms:	39,000	65,900	175,000	161,400	203,300	37,500	60,300	157,100	147,600	185,300
Natural gas*, MBtu:	3,900	6,590	17,500	16,140	20,330	3,750	6,030	15,710	14,760	18,530
Emission, lb										
Particulate matter	29	49	130	120	151	28	45	117	110	138
CO_2	459,000	775,000	2,059,000	1,899,000	2,392,000	441,000	709,000	1,848,000	1,736,000	2,180,000
SO_2	2	4	10	9	12	2	4	9	9	11
NO_x	359	607	1,613	1,487	1,874	346	556	1,448	1,360	1,708
VOC	21	36	94	87	110	20	33	85	80	100
CO	153	258	686	633	797	147	236	616	579	727
CH_4	9	15	39	36	46	8	14	35	33	42

*Natural gas burned in furnace and water heater.
Source: Reference 14.

Table 5-10A. Transportation Emissions from Transporting Materials to and from House Site – SI Units

	Wood frame house					ICF house				
	Miami	Phoenix	Seattle	DC	Chicago	Miami	Phoenix	Seattle	DC	Chicago
Emission, kg										
Particulate matter	2	2	2	2	2	4	4	4	4	4
CO_2	1,440	1,500	1,500	1,620	1,860	2,770	2,830	2,830	2,950	3,190
SO_2	2	2	2	3	3	4	4	4	5	5
NO_x	13	14	14	15	17	25	26	26	27	29
VOC	2	2	2	3	3	5	5	5	5	5
CO	13	14	14	15	17	25	26	26	27	29
CH_4	0	0	0	0	1	1	1	1	1	1

*Fuel efficiency is 24 liters of diesel fuel per 1000 metric ton-kilometers.
Source: Reference 12.

Table 5-10B. Transportation Emissions from Transporting Materials to and from House Site – U.S. Customary Units

	Wood frame house					ICF house				
	Miami	Phoenix	Seattle	DC	Chicago	Miami	Phoenix	Seattle	DC	Chicago
Emission, lb										
Particulate matter	4	4	4	5	5	8	8	8	8	9
CO_2	3,170	3,310	3,310	3,570	4,110	6,100	6,230	6,230	6,500	7,030
SO_2	5	5	5	6	7	10	10	10	10	11
NO_x	29	30	30	33	38	56	57	57	60	65
VOC	5	5	5	6	7	10	10	10	11	12
CO	29	30	30	33	38	56	57	57	60	64
CH_4	1	1	1	1	1	2	2	2	2	2

*Fuel efficiency is 9.4 of gallon diesel fuel per 1000 ton miles.
Source: Reference 12.

Table 5-11A. Summary of 100-Year Life Cycle Emissions – SI Units*

	Wood frame house					ICF house				
	Miami	Phoenix	Seattle	DC	Chicago	Miami	Phoenix	Seattle	DC	Chicago
Emission, kg										
Particulate matter	48	59	96	97	121	106	116	149	151	174
CO_2	216,000	360,000	942,000	870,000	1,096,000	222,000	344,000	860,000	810,000	1,014,000
SO_2	33	36	39	43	54	87	90	92	97	108
NO_x	204	320	775	724	910	260	358	762	728	897
VOC	13	20	46	43	54	17	23	46	44	54
CO	87	136	330	307	385	104	146	318	303	373
CH_4	5	8	19	18	22	6	8	18	17	21

*Does not include upstream profile of electricity, fuel, or materials other than concrete.

Table 5-11B. Summary of 100-Year Life Cycle Emissions – U.S. Customary Units*

	Wood frame house					ICF house				
	Miami	Phoenix	Seattle	DC	Chicago	Miami	Phoenix	Seattle	DC	Chicago
Emission, lb										
Particulate matter	105	131	212	214	268	233	256	328	332	383
CO_2	477,000	795,000	2,079,000	1,921,000	2,419,000	489,000	758,000	1,897,000	1,788,000	2,237,000
SO_2	73	80	86	96	120	191	198	204	214	237
NO_x	451	705	1,711	1,598	2,008	573	790	1,682	1,606	1,978
VOC	29	44	102	96	120	37	50	102	98	120
CO	192	299	727	678	850	230	321	701	668	824
CH_4	11	17	42	39	49	13	18	40	38	47

*Does not include upstream profile of electricity, fuel, or materials other than concrete.

No data are available on waste heat from other stages of concrete manufacturing process. The waste heat associated with house heating and cooling and other occupant uses is not considered significant and is not included in this LCI.

5.5. Sensitivity

The house life cycle energy is not sensitive to variations in cement manufacturing or concrete production. Approximately 99% of the house life cycle energy is occupant energy-use, that is, energy for heating, cooling, lighting, washing, and other uses. Approximately 1% of the house life cycle energy is the energy embodied in the concrete portion of the house. Furthermore, about 70% of the energy embodied in concrete is from cement manufacturing.[4] To put this into perspective, consider the life cycle energy use of the ICF house in Chicago: the embodied energy of the concrete is equivalent to the energy savings from using the temperature set backs described in Section 4 for 17 years. The set back consists of raising the cooling set-point temperature by 2°C (3°F) at night and decreasing the heating set-point by 3°C (5°F) at night. Furthermore, after climate, occupant behavior is the single most important factor contributing to energy consumption in a home.[18] Therefore, the house life cycle energy use is a function of climate and occupant behavior, not concrete content.

6. SUMMARY AND CONCLUSIONS

A partial LCI of a wood frame house and an ICF house has been carried out according to SETAC guidelines and ISO standards 14040 and 14041. The house was modeled in five cities, representing a range of U.S. climates: Phoenix, Miami, Washington, Seattle, and Chicago.

The house is a two-story single-family building with a contemporary design. The house system boundary includes the energy and material inputs and outputs of excavation; construction; occupancy; maintenance, repair, and replacement; demolition; and disposal. The partial LCI is presented in terms of energy use, material use, emissions to air, and solid waste generation over a 100-year life. It also includes the upstream profile of concrete and the masses of other building materials used in the house.

This partial LCI does not include the emissions from the manufacture of other building materials like wood, steel, and plastic. It also does not include the upstream profile of fuel and electricity production and distribution. Furthermore, the LCI does not include inputs that (i) are less than 1% of the total mass of the processed materials or product, (ii) do not contribute significantly to a toxic emission, and (iii) do not have a significant associated energy consumption.

The results show that occupant energy-use accounts for 99% of life cycle energy-use of the ICF house and wood frame house. This means that less than 1% of the life cycle energy is due to cement manufacturing and concrete production. The house life cycle energy is primarily a function of climate and occupant behavior, not concrete content. Therefore, the ICF house, which is more energy-efficient than the wood frame house, has a lower life cycle energy-use. Furthermore, although the ICF house contains more embodied energy than the wood frame house, after 5 years in Chicago, for example, the cumulative energy use of the wood frame house surpasses that of the ICF house.

This partial LCI includes emissions to air of greenhouse gases and the most common air pollutants as defined by United Sates Environmental Protection Agency. These emissions consist of particulate matter from point and fugitive sources and the following combustion gases: carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOC), and methane (CH_4). Hazardous air pollutants, such as hydrogen chloride, mercury, dioxins, and furans, are excluded from the house LCI because there is insufficient information to accurately quantify their emission from the manufacture of cement.

Most of the life cycle emissions to air are mainly from the two natural gas burning appliances (furnace and water heater). Most of the particulate matter (60%) and SO_2 emissions (89%) are from the manufacture of concrete. Most of the emissions of CO_2 (97%), NO_x (83%), CO (85%), VOC (80%), and CH_4 (86%) are from the combustion of household natural gas for heating and hot water.

In the next phase of the project, PCA will include the upstream profiles of other materials, such as wood and steel, and fuels, such as coal and electricity, in the house LCI. The ultimate goal is to use the LCI data to conduct a life cycle assessment (LCA) of the wood frame house and ICF house. The LCA will quantify the impacts of concrete products on the environment, such as climate change, acidification, nutrification, natural resource depletion, and risks to human health and other ecological consequences.

7. ACKNOWLEDGEMENT

The research reported in this paper (PCA R&D Serial No. 2464) was conducted by Construction Technology Laboratories, Inc. and Jan Consultants, with the sponsorship of the Portland Cement Association (PCA Project Index No. 94-04). The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data presented. The contents do not necessarily reflect the views of the Portland Cement Association.

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APPENDIX A – TARGET AUDIENCES AND INFORMATION TO BE COMMUNICATED

This report is one of many for the Environmental Life Cycle Assessment (LCA) of Portland Cement Concrete project sponsored by the Portland Cement Association.

The objectives of publishing reports and disseminating information are to:

- Determine the environmental life cycle benefits associated with the use of these products.
- Produce comparisons of concrete and other building materials.
- Provide information about these benefits to manufacturers and users of these products.
- Provide life cycle inventory (LCI) and LCA information to practitioners and others, such as data base providers in need of accurate data on cement and concrete.

The contents of the reports will provide information for the following audiences:

- Members of the Portland Cement Association (PCA) and other organizations that promote the use of cement and concrete, generally called “allied industries.”
- Members of the Environmental Council of Concrete Organizations (ECCO).
- LCA practitioners and database developers.
- Engineers, architects, and designers.
- Public agencies (Departments of Transportation [DOTs], Energy Star, Environmentally Preferable Purchasing Program).
- General public.

The report formats are not particularly suited for all audiences. The reports are intended to document the particular partial LCI, LCI, or LCA. They provide data in a transparent, traceable format for documentation purposes. The intent is that abbreviated papers, brochures, data packages, presentations, or press releases can be developed from the project reports. The materials presenting the results of this project will be matched, in form and format, to the needs of the target audience. The materials have been categorized as follows:

- General Information:
    - Purpose of life cycle assessments (LCAs) and how they are done.
    - Limited life cycle results of portland cement concrete products from production through use to demolition and recycling.
- Summary Results:
    - Presentation of selected life cycle inventory (LCI) data in the form of summary information, bar charts or other diagrams; for example PowerPoint™ presentations.
    - Published papers or articles.
- Detailed Results:
    - LCI results for databases or LCA models, such as BEES or Athena.
    - Description of the LCI methodology used in the project and specific assumptions, information sources/references, and detailed results.

APPENDIX B – HOUSE PLANS AND WALL CROSS-SECTIONS

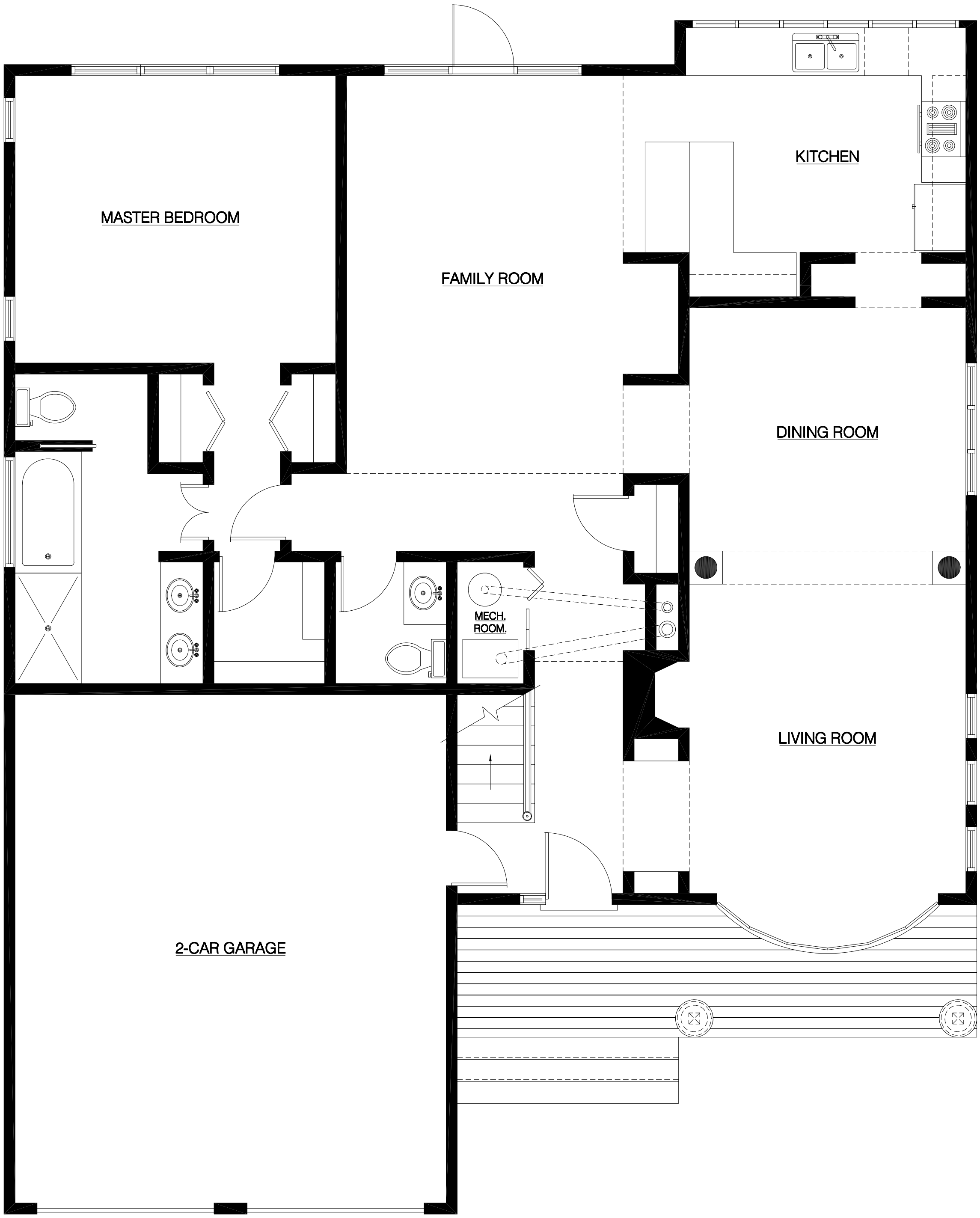

Figure B-1. Floor plan of the lower level.

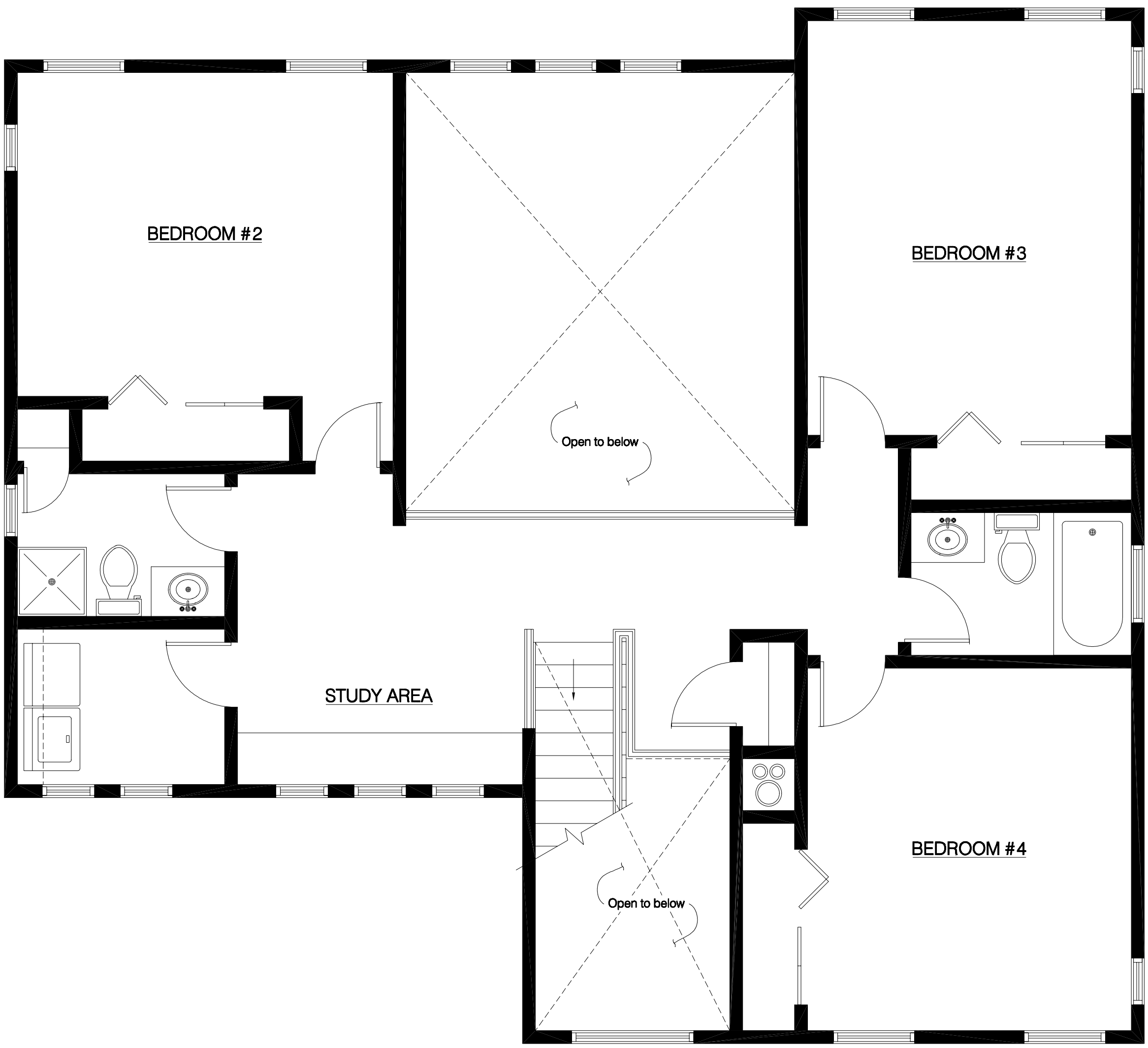

Figure B-2. Floor plan of the upper level.

Figure B-3. Front elevation.

Figure B-4. Rear elevation.

Figure B-5. Right elevation.

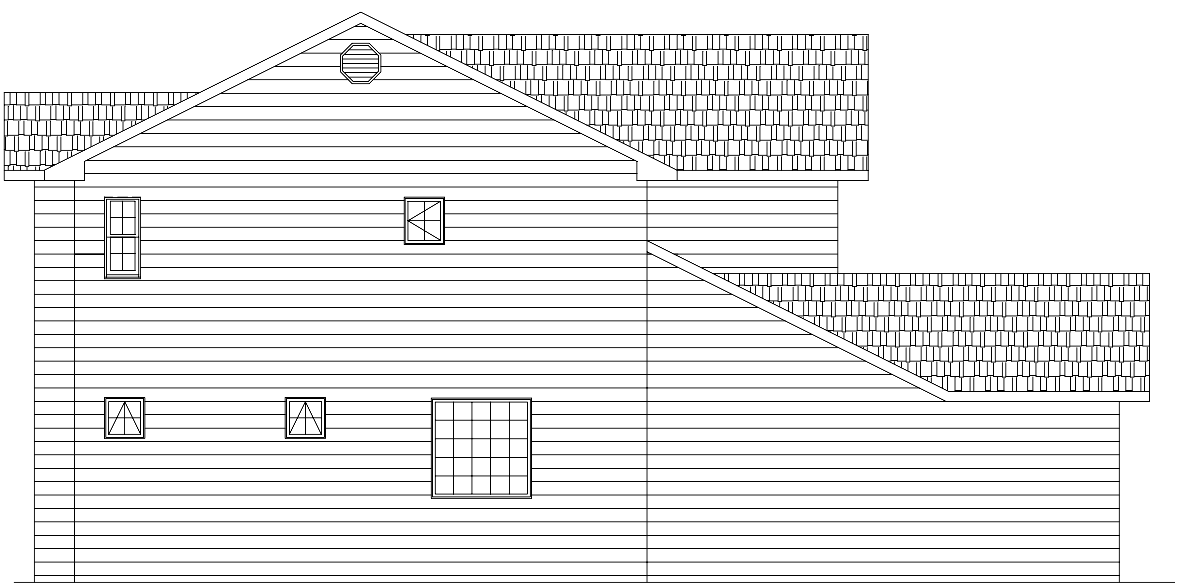

Figure B-6. Left elevation.

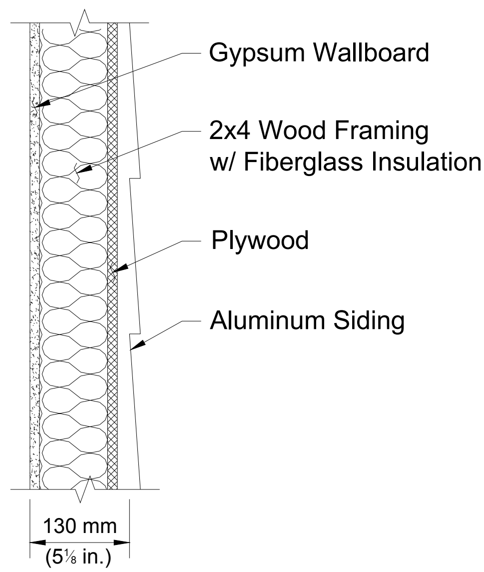

Figure B-7. Wood frame wall cross-section.

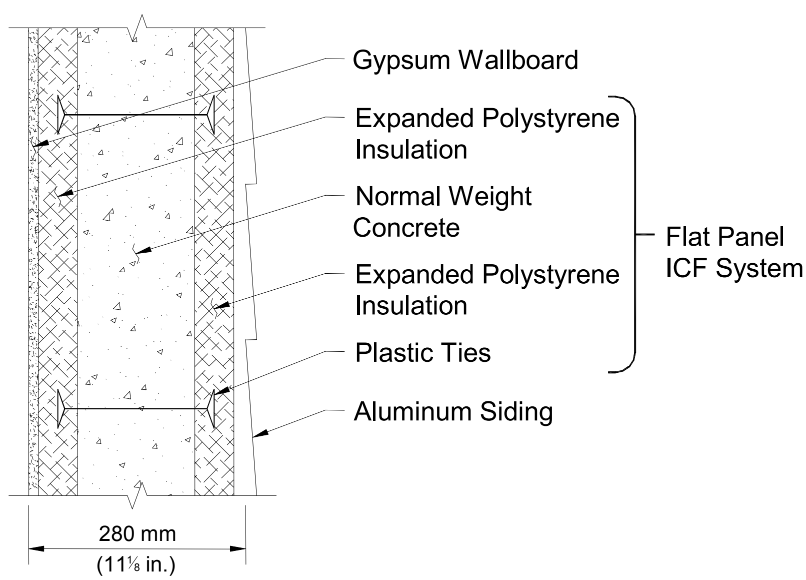

Figure B-8. ICF wall cross-section.

APPENDIX C – MATERIALS LIST

Table C-1A. House Materials List – SI Units*

	Wood frame house					ICF house				
Material, kg	**Miami**	**Phoenix**	**Seattle**	**DC**	**Chicago**	**Miami**	**Phoenix**	**Seattle**	**DC**	**Chicago**
Ready-mixed concrete	70,661	76,166	76,166	87,177	109,198	193,725	199,230	199,230	210,241	232,262
Fiber-cement backer board	1,545	1,545	1,545	1,545	1,545	1,545	1,545	1,545	1,545	1,545
Metal	3,453	3,523	3,523	3,665	3,949	5,015	5,086	5,086	5,228	5,512
Aluminum	849	849	849	849	849	849	849	849	849	849
Copper	67	67	67	67	67	67	67	67	67	67
Galvanized steel	310	310	310	310	310	310	310	310	310	310
Sheet metal	372	372	372	372	372	372	372	372	372	372
Steel	1,854	1,925	1,925	2,066	2,350	3,416	3,487	3,487	3,629	3,913
Wood	20,400	20,400	20,400	20,400	20,400	17,211	17,211	17,211	17,211	17,211
Framing	10,753	10,753	10,753	10,753	10,753	7,860	7,860	7,860	7,860	7,860
Treated	676	676	676	676	676	2,001	2,001	2,001	2,001	2,001
Plywood	5,040	5,040	5,040	5,040	5,040	4,446	4,446	4,446	4,446	4,446
Sheathing	1,027	1,027	1,027	1,027	1,027	0	0	0	0	0
Miscellaneous	2,904	2,904	2,904	2,904	2,904	2,904	2,904	2,904	2,904	2,904
Gypsum wallboard	8,896	8,896	8,896	8,896	8,896	9,662	9,662	9,662	9,662	9,662
Insulation, expanded polystyrene	0	30	30	90	209	1,922	1,952	1,952	2,012	2,131
Insulating concrete form	0	0	0	0	0	1,922	1,922	1,922	1,922	1,922
Other	0	30	30	90	209	0	30	30	90	209
Insulation, fiberglass	429	544	544	544	627	211	326	326	326	409
Polymers	10,243	10,243	10,243	10,243	10,243	10,072	10,072	10,072	10,072	10,072
Carpet and pad	6,421	6,421	6,421	6,421	6,421	6,421	6,421	6,421	6,421	6,421
Linoleum	364	364	364	364	364	364	364	364	364	364
Paint	2,690	2,690	2,690	2,690	2,690	2,690	2,690	2,690	2,690	2,690
Polyester fabric	22	22	22	22	22	0	0	0	0	0
PVC	430	430	430	430	430	430	430	430	430	430
Sealant	299	299	299	299	299	150	150	150	150	150
General	16	16	16	16	16	16	16	16	16	16
Roofing materials	5,827	5,827	5,827	5,827	5,827	5,827	5,827	5,827	5,827	5,827
Windows	3,128	3,128	3,128	3,128	3,128	3,128	3,128	3,128	3,128	3,128
Tile	3,641	3,641	3,641	3,641	3,641	3,641	3,641	3,641	3,641	3,641
Lighting products	577	577	577	577	577	577	577	577	577	577
Electrical wire	111	111	111	111	111	111	111	111	111	111
Shipping weight, various**	5,470	5,470	5,470	5,470	5,470	5,470	5,470	5,470	5,470	5,470
Total (rounded)	**134,400**	**140,100**	**140,100**	**151,300**	**173,800**	**258,100**	**263,800**	**263,800**	**275,000**	**297,600**

*Includes items replaced during 100-year life.

**See Table C-2 in Appendix C for a listing of other items that contribute to shipping weight.

Table C-1B. House Materials List – U.S. Customary Units*

	Wood frame house					ICF house				
Material, lb	**Miami**	**Phoenix**	**Seattle**	**DC**	**Chicago**	**Miami**	**Phoenix**	**Seattle**	**DC**	**Chicago**
Ready-mixed concrete	155,780	167,918	167,918	192,192	240,741	427,090	439,227	439,227	463,501	512,050
Fiber-cement backer board	3,406	3,406	3,406	3,406	3,406	3,406	3,406	3,406	3,406	3,406
Metal	7,611	7,768	7,768	8,081	8,706	11,056	11,213	11,213	11,525	12,151
Aluminum	1,873	1,873	1,873	1,873	1,873	1,873	1,873	1,873	1,873	1,873
Copper	147	147	147	147	147	147	147	147	147	147
Galvanized steel	684	684	684	684	684	684	684	684	684	684
Sheet metal	821	821	821	821	821	821	821	821	821	821
Steel	4,086	4,243	4,243	4,555	5,181	7,531	7,688	7,688	8,000	8,626
Wood	44,975	44,975	44,975	44,975	44,975	37,944	37,944	37,944	37,944	37,944
Framing	23,707	23,707	23,707	23,707	23,707	17,328	17,328	17,328	17,328	17,328
Treated	1,489	1,489	1,489	1,489	1,489	4,412	4,412	4,412	4,412	4,412
Plywood	11,111	11,111	11,111	11,111	11,111	9,802	9,802	9,802	9,802	9,802
Sheathing	2,265	2,265	2,265	2,265	2,265	0	0	0	0	0
Miscellaneous	6,402	6,402	6,402	6,402	6,402	6,402	6,402	6,402	6,402	6,402
Gypsum wallboard	19,612	19,612	19,612	19,612	19,612	21,301	21,301	21,301	21,301	21,301
Insulation, expanded polystyrene	0	66	66	198	461	4,237	4,303	4,303	4,435	4,699
Insulating concrete form	0	0	0	0	0	4,237	4,237	4,237	4,237	4,237
Other	0	66	66	198	461	0	66	66	198	461
Insulation, fiberglass	946	1,198	1,198	1,198	1,382	466	719	719	719	902
Polymers	22,583	22,583	22,583	22,583	22,583	22,204	22,204	22,204	22,204	22,204
Carpet and pad	14,156	14,156	14,156	14,156	14,156	14,156	14,156	14,156	14,156	14,156
Linoleum	803	803	803	803	803	803	803	803	803	803
Paint	5,931	5,931	5,931	5,931	5,931	5,931	5,931	5,931	5,931	5,931
Polyester fabric	49	49	49	49	49	0	0	0	0	0
PVC	949	949	949	949	949	949	949	949	949	949
Sealant	659	659	659	659	659	330	330	330	330	330
General	35	35	35	35	35	35	35	35	35	35
Roofing materials	12,847	12,847	12,847	12,847	12,847	12,847	12,847	12,847	12,847	12,847
Windows	6,896	6,896	6,896	6,896	6,896	6,896	6,896	6,896	6,896	6,896
Tile	8,026	8,026	8,026	8,026	8,026	8,026	8,026	8,026	8,026	8,026
Lighting products	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272
Electrical wire	245	245	245	245	245	245	245	245	245	245
Shipping weight, various**	12,058	12,058	12,058	12,058	12,058	12,058	12,058	12,058	12,058	12,058
Total (rounded)	**296,300**	**308,900**	**308,900**	**333,600**	**383,200**	**569,000**	**581,700**	**581,700**	**606,400**	**656,000**

*Includes items replaced during 100-year life.

**See Table C-2 in Appendix C for a listing of other items that contribute to shipping weight.

Table C-2A. Items that Contribute to Shipping Weight and their Replacement Schedule – SI Units*

Item	Quantity	Weight*, kg	Replacement schedule	100-year weight, kg
Fiberglass column, exterior non-structural	2	54	none	54
Medicine cabinet w/ mirror	3	36	25	144
Range, 75 cm wide, natural gas	1	100	15	699
Dishwasher, 60 cm wide	1	45	15	318
Refrigerator, 90 cm wide	1	159	15	1,111
Washer & dryer (set)	1	113	15	794
Toilet, two piece tank type	4	65	25	261
Lavatory, synthetic marble w/ drain and faucet	5	87	25	348
Shower base, fiberglass w/ drain and faucet	2	27	25	109
Bathtub w/ shower, steel w/ drain and faucet	2	93	25	370
Double bowl kitchen sink, steel w/ drains and faucets	1	19	25	77
Garbage disposal	1	6	20	28
Domestic water heater, natural gas, 28 liters	1	45	20	227
Furnace, natural gas	1	73	20	363
Air conditioner, electric	1	113	20	567
Total		**1,036**		**5,470**

*Includes packaging materials.

Table C-2B. Items that Contribute to Shipping Weight and their Replacement Schedule – U.S. Customary Units*

Item	Quantity	Weight*, lb	Replacement schedule	100-year weight, lb
Fiberglass column, exterior non-structural	2	120	none	120
Medicine cabinet w/ mirror	3	79	25	317
Range, 30" wide, natural gas	1	220	15	1,540
Dishwasher, 24" wide	1	100	15	700
Refrigerator, 36" wide	1	350	15	2,450
Washer & dryer (set)	1	250	15	1,750
Toilet, two piece tank type	4	144	25	576
Lavatory, synthetic marble w/ drain and faucet	5	192	25	767
Shower base, fiberglass w/ drain and faucet	2	60	25	240
Bathtub w/ shower, steel w/ drain and faucet	2	204	25	816
Double bowl kitchen sink, steel w/ drains and faucets	1	43	25	170
Garbage disposal	1	13	20	63
Domestic water heater, natural gas, 75 gallons	1	100	20	500
Furnace, natural gas	1	160	20	800
Air conditioner, electric	1	250	20	1,250
Total		**2,284**		**12,058**

*Includes packaging materials.

APPENDIX D – FUEL AND ELECTRICITY USE

Table D-1A. Life Cycle Fuel and Electricity Use – SI Units*

	Wood frame house					ICF house				
	Miami	**Phoenix**	**Seattle**	**DC**	**Chicago**	**Miami**	**Phoenix**	**Seattle**	**DC**	**Chicago**
Fuel input, unit										
Coal, kg	789	850	850	973	1219	2162	2224	2224	2347	2592
Gasoline, L	0.38	0.41	0.41	0.47	0.59	1.05	1.08	1.08	1.14	1.26
Liquefied petroleum gas, L	0.12	0.13	0.13	0.15	0.18	0.32	0.33	0.33	0.35	0.39
Diesel fuel, L	835	882	882	973	1158	1857	1903	1903	1995	2180
Natural gas, m^3	0.11	0.19	0.50	0.46	0.58	0.11	0.17	0.45	0.42	0.53
Petroleum coke, kg	157	169	169	193	242	430	442	442	466	515
Residual oil, L	1.20	1.29	1.29	1.48	1.85	3.29	3.38	3.38	3.57	3.94
Wastes, kg	127	137	137	157	197	349	359	359	379	419
Electricity, 1000 kWh	1815	2102	986	1209	1157	1703	1955	965	1157	1111
Energy input, GJ										
Coal	21	23	23	27	33	59	61	61	64	71
Gasoline	0.013	0.014	0.014	0.017	0.021	0.037	0.038	0.038	0.040	0.044
Liquefied petroleum gas	0.003	0.003	0.003	0.003	0.004	0.008	0.008	0.008	0.008	0.009
Diesel fuel	32	34	34	38	45	72	73	73	77	84
Natural gas	4,119	6,957	18,468	17,033	21,455	3,967	6,373	16,586	15,584	19,563
Petroleum coke	5	6	6	7	8	15	15	15	16	18
Residual oil	0.049	0.053	0.053	0.061	0.076	0.135	0.139	0.139	0.147	0.162
Wastes	3	3	3	4	5	8	8	8	9	10
Electricity	6,533	7,567	3,548	4,351	4,164	6,130	7,037	3,475	4,164	4,001
Total energy input (rounded)	**10,700**	**14,600**	**22,100**	**21,500**	**25,700**	**10,300**	**13,600**	**20,200**	**19,900**	**23,700**

*Does not include upstream profile of electricity, fuel, or materials other than concrete.

Table D-1B. Life Cycle Fuel and Electricity Use – US Customary Units*

	Wood frame house					ICF house				
	Miami	**Phoenix**	**Seattle**	**DC**	**Chicago**	**Miami**	**Phoenix**	**Seattle**	**DC**	**Chicago**
Fuel input, unit										
Coal, ton	0.87	0.94	0.94	1.07	1.34	2.38	2.45	2.45	2.59	2.86
Gasoline, gallon	0.10	0.11	0.11	0.13	0.16	0.28	0.29	0.29	0.30	0.33
Liquefied petroleum gas, gallon	0.03	0.03	0.03	0.04	0.05	0.09	0.09	0.09	0.09	0.10
Diesel fuel, gallon	221	233	233	257	306	491	503	503	527	576
Natural gas, million ft^3	3.90	6.59	17.50	16.14	20.34	3.76	6.04	15.72	14.77	18.54
Petroleum coke, ton	0.17	0.19	0.19	0.21	0.27	0.47	0.49	0.49	0.51	0.57
Residual oil, gallon	0.32	0.34	0.34	0.39	0.49	0.87	0.89	0.89	0.94	1.04
Wastes, ton	0.14	0.15	0.15	0.17	0.22	0.39	0.40	0.40	0.42	0.46
Electricity,1000 kWh	1815	2102	986	1209	1157	1703	1955	965	1157	1111
Energy input, MBtu										
Coal	20	22	22	25	31	56	57	57	61	67
Gasoline	0.013	0.014	0.014	0.016	0.020	0.035	0.036	0.036	0.038	0.042
Liquefied petroleum gas	0.003	0.003	0.003	0.003	0.004	0.007	0.008	0.008	0.008	0.009
Diesel fuel	31	32	32	36	42	68	70	70	73	80
Natural gas	3,904	6,594	17,504	16,145	20,336	3,760	6,041	15,721	14,771	18,542
Petroleum coke	5	5	5	6	8	14	14	14	15	17
Residual oil	0.047	0.050	0.050	0.058	0.072	0.128	0.132	0.132	0.139	0.154
Wastes	3	3	3	3	4	8	8	8	8	9
Electricity	6,192	7,172	3,363	4,124	3,947	5,810	6,670	3,294	3,947	3,792
Total energy input (rounded)	**10,200**	**13,800**	**20,900**	**20,300**	**24,400**	**9,700**	**12,900**	**19,200**	**18,900**	**22,500**

*Does not include upstream profile of electricity, fuel, or materials other than concrete.