LIFE-CYCLE ASSESSMENT AND LIFE-CYCLE COST AS COLLABORATIVE TOOLS IN RESIDENTIAL HEATING SYSTEM SELECTION

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ABSTRACT

Typically the selection of a residential heating system focuses on first costs rather than the economic or environmental life cycle consequences. The use of life cycle assessment and life cycle cost methodologies in the design phase provide additional criteria for consideration when selecting a residential heating system. A comparative case study of a gas forced air and radiant solar heating system was conducted for a 3,000 square foot house located in Fort Collins, Colorado, U.S.A. The initial results of an analysis of the life cycle assessment and the life cycle cost data indicated the gas forced air system was superior, both environmentally and economically. Further data analysis pinpointed solar radiant system components for replacement in an effort to reduce both life cycle environmental emissions and costs. This analysis resulted in a hybrid radiant system using a high-efficiency gas-fired boiler, a choice that lowered both the solar radiant system's costs and emissions. This new system had slightly lower environmental impacts than both the gas forced air system and solar radiant system. Unfortunately the hybrid system had less impact on the life cycle cost with the hybrid system substantially more expensive then the gas-forced air alternative.

KEYWORDS

life cycle cost, LCC, life cycle assessment, LCA, residential heating systems

INTRODUCTION

The impact of the residential housing market on emissions in the United States of America (US) is significant. An analysis of 1997 data revealed that the new single-unit residential sector accounted for 5% of the US Global Warming Potential (GWP) emissions generated (Hendrickson & Horvath, 2000). Out of all global greenhouse gas (GHG) emissions, CO_2 is the predominant GHG contributing 76.7% of all global GHG emissions in 2004 (IPCC, 2007). The US is not alone in its substantial generation of GHG. China became the world leader in total CO_2 fossil fuel emissions in 2006 producing 1,665 million metric tons (MMT) surpassing the US CO_2 total fossil-fuel emissions of 1,569 MMT (Boden, Marland, & Andres, 2009). The combustion of fossil fuels is the largest source of CO_2 emissions and the US is a world leader in CO_2 emissions per capita. In 2005, the US produced 24% of global CO_2 emissions; an amount five times the world average of CO_2 emissions per capita (World Bank, n.d.). The Census Bureau estimates that there were 124.5 million homes in the US in 2005 (US Census Bureau, 2006). With the US population expected to grow to an estimated 363.5 million by 2030 or 63.5 million more than in 2006, 14.54 million new homes will need to be built; based on an average family size of 2.5 persons (US Census Bureau, 2005).

Research Question

The population projections for the US indicate that there will be a need for new residential housing units in the future even as the housing markets adjust to current financial drivers. The form of housing unit, single family or high density, new or remodeled, doesn't matter if each unit contains an individual heat source venting emissions to the outside. What

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is of concern is the ability to look at each project in an objective manner and identify a heating system that best fits the project goals while producing the lowest emissions. This study compared the life cycle environmental impacts and life cycle costs (LCC) of a residential gas-forced air and residential solar hot water radiant heat system for a single family home in Fort Collins, Colorado, US. Once these heating systems are analyzed for environmental and economic impacts, hybrid systems can be created in an effort to minimize both environmental and economic impacts.

Significance

In Colorado, the 2002 CO_2 emissions from fossil fuel consumption in the residential sector amounted to 7.49 MMT (US Environmental Protection Agency (EPA), n.d.). The population in Colorado from 2000 to 2030 is projected to increase by 1.491 million people (US Census Bureau, 2005). Based on the average family size of 2.5 people, this equates to 569,400 new homes by 2030. It is in the design phase where decisions are made that impact every phase in the residential construction process. One of the most important concepts in design is to reduce the loads placed on systems. Some of the common ways this is achieved is proper building orientation, reduced size, and an efficient building envelope. The decisions made in all phases of a building's life need to be ascertained from a practical, economically responsible, and timeliness point of view (Morrissey, O'Donnell, Keane & Bazjanac, 2004). Schenek (2005) argues that not measuring the environmental performance of a decision could result in spending money on items that do not matter. Since "the average single-family home adds more than twice as much GHG emissions to the atmosphere as the average passenger vehicle" (US EPA, pg.6, 2004), homeowners and residential construction and design professionals need to understand all of the life cycle consequences of heating systems.

LITERATURE REVIEW

Heating Systems

Two heating systems were studied: gas forced air (GFA) and solar radiant heat system (SRS). GFA systems typically consist of a heat exchanger and fan/blower (furnace), and ductwork. The indoor air is moved over the gas fired heat exchanger and circulated throughout the building and then returned through ductwork to repeat the process; a thermostat controls the furnace operation. The SRS system consists of a thermal solar collector, hot water storage tank, circulator pumps, and a piped distribution system either placed under the floor or through fin type radiators (there are several delivery methods). During daylight hours the solar collectors heat water that is circulated through storage tanks for heating in non-daylight hours. The pipe distribution system typically is made up of a series of zones, with each zone having its own thermostat and control system. When heat is needed, the thermostat opens the zone valve and turns on a circulation pump. Hot water is circulated through that zone's piping system until the desired temperature is reached. The zone valve is then closed and the circulation pump is turned off.

Life Cycle Cost (LCC)

Life cycle methodologies stem from life cycle thinking where the impacts of a process, product, or system are evaluated in all life cycle phases to ascertain a total impact. "The LCC is the total cost of owning, operating, maintaining, and (eventually) disposing of the building system(s) over a given study period (usually related to the life of the project), with all costs adjusted (discounted) to reflect the time value of money" (Fuller & Petersen, pg.1-2, 1995). LCC has been, and continues to be, the current industry standard for assessing total financial impacts over the service life of a product, in which service life is defined as the length of time during which a product can be used. In addition to the cost of owning, operating, maintaining and disposing of a product, LCC may also include a salvage value.

Life Cycle Assessment (LCA)

For the LCA method, the environmental impacts emanate from five phases: material extraction/conversion, manufacturing, maintenance/use, and disposal/reuse (Fava et al., 1991; Curran, 1996; Tibor & Feldman, 1996). The environmental emissions and energy use from all life cycle phases can be identified to determine the total environmental impacts for a product or process. Figure 1 shows the life cycle phases for residential heating systems in which

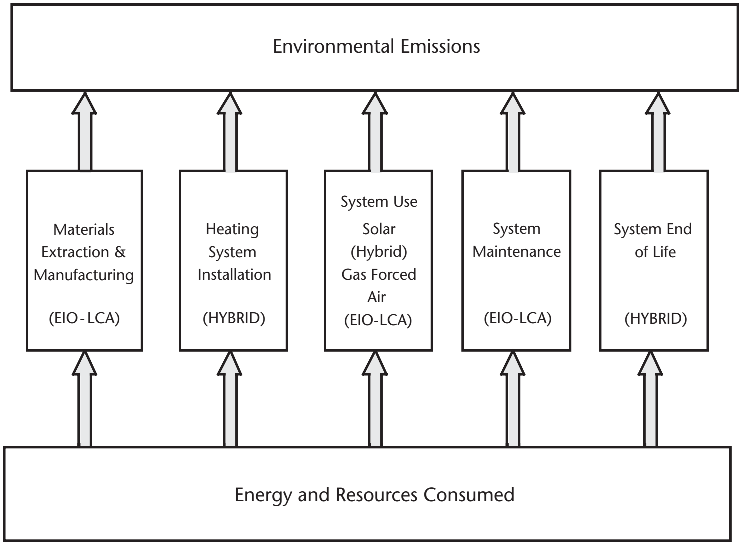

FIGURE 1. Residential heating systems life-cycle phases. (Source: Adapted from Guggemos, 2003). Note: items in parentheses indicate the LCA method used in this study.

heating system installation at the jobsite is a separate phase from the materials extraction and manufacturing that occur prior to the system being shipped to the jobsite.

Traditional process-based LCA emerged in the manufacturing field and is now the preferred methodology to use in the construction industry for the environmental assessment of alternative choices (Treloar, Love, Faniran, & Iyer-Raniga, 2000). This method requires setting a study boundary to identify what will be included in the study. The study boundary is often determined based on the availability of funds, time, and proprietary information. An alternative LCA methodology, Economic Input/Output LCA (EIO-LCA), expands the study boundary to include upstream supply chain impacts within the US economy (Hendrickson, Lave, & Matthews, 2006) and reduces the impacts of time, cost, and proprietary issues that affect traditional process-based LCA. However, this methodology is based on aggregated economic information from the Department of Commerce and may not accurately represent a specific product or process being studied. There are also concerns that the construction and end-of-life phases are not represented by the data (Hendrickson et al., 2006). If it is apparent that the EIO-LCA data is too aggregated or missing for a particular phase, traditional process-based LCA can be applied in an effort to provide the specific data required. By using the strengths of each LCA methodology in combination, a hybrid LCA method is created and the weaknesses of each individual method are somewhat minimized (Hendrickson et al., 2006).

Life Cycle Assessment Applications in the Built Environment

Some LCA studies focus on the construction industry. Horvath (1997) used EIO-LCA to look at the design and material use of steel and concrete bridge girders, asphalt and concrete pavement, and wood and light gauge metal residential framing. Guggemos (2003) focused on the construction phase of steel and concrete building structures. Blanchard and Reppe (1998) performed an LCA of a single-family residence in Michigan. Yang (2005) studied residential heating systems in Canada using similar delivery systems: hot water baseboard and gas forced air. The study was limited to the production, construction and operation phases. This study focuses on all five phases and was performed during the design phase of the construction process.

METHODOLOGY

This study used both LCA and LCC methodologies in the evaluation of residential heating systems. LCA and LCC are both rational and systematic methods used to analyze environmental and economic impacts of decisions, respectively. Although each methodology is the “preferred method” it is important to understand the strengths and weaknesses of each method. The EIO-LCA methodology is linear in nature and uses aggregated data from 1997. The hybrid LCA approach used in this study builds on the strengths of both the traditional process-based LCA and EIO-LCA while minimizing the weaknesses of either approach used independently. Figure 1, previously discussed, identifies the LCA method used for each life cycle phase. The EIO-LCA calculations were performed using the eiolca.net website developed by the Carnegie Mellon University Green Design Institute (2009). Although EIO-LCA calculates emissions based on costs, note that a decrease in cost will not necessarily result in a decrease in emissions. For the construction and end-of-life phases, process diagrams were created for each heating system by phase and the energy use and emissions data were derived from past research (see Glick, 2007; Glick & Guggemos, 2007).

A major weakness of LCC is the ability to accurately predict prices of multiple variables into the future. This is especially difficult during periods of inflation and instability of fuel supplies. However, the use of LCA and LCC in a comparative study reduces the implications of their weaknesses. This is due to the same assumption being made for each product being compared. The US Department of Energy's (DOE) Building Life Cycle Cost Program (BLCC 5.3) developed by the National Institute of Standards and Technology was used for the LCC calculations (US DOE, n.d.).

Data Collection and Rationale

The data requirements for the EIO-LCA include a detailed list of system components and associated costs, North American Industry Classification System (NAICS) categories, a discounting mechanism to take current year dollars to base year (1997) dollars, and the producer costs. The installed cost for the GFA system was bid as a lump sum and RS Means was used to create a detailed component list with associated costs and estimated labor, profit and overhead (RS Means, 2006). This detailed estimate was reviewed by industry professionals for accuracy. The professionals are practitioners in the GFA industry and are considered regional leaders in their field. The uninstalled cost for the SRS was bid in detailed line item form. RS Means was used to estimate the installation costs (RS Means, 2006).

For the phases using the EIO-LCA method, the component descriptions and costs were then assigned NAICS numbers. Each NAICS category represents one of 485 sectors of the US economy assigned by the US Department of Commerce (DOC). The NAICS category numbers are available on the DOC website and on the eiolca.net website. This step ensures that the component parts are represented by industry categories.

To use the EIO-LCA data, the current cost must be adjusted to the producer cost. To do this, an analysis of each mark-up in the supply chain must be performed. Each markup is then deducted from the cost to reach the producer cost. These costs are in current year dollars. The values used in the eiolca.net software are from 1997; therefore the current costs need to be deflated to the base year (1997). Once this is done, the eiolca.net software can be used to estimate values for energy use and global warming potential (GWP) emissions for the materials extraction and manufacturing, system use, and system maintenance phases. GWP is the sum of all the CO_2 equivalents (CO_2E) of CO_2, CH_4, N_2O, and HFC/PFC emissions.

The data collection for the construction and end-of-life phases was based on traditional process diagrams to overcome data aggregation or missing data in the EIO-LCA data sets. Four separate process diagrams were created: GFA installation, GFA end of life, SRS installation, and SRS end of life. Reference Glick and Guggemos (2007) for the full process diagrams. Each diagram includes activities that occur at the jobsite as well as offsite activities, particularly transportation of materials, equipment, and installers to and from the jobsite. Durations were estimated using RS Means and the resulting emissions were estimated based on past research (Glick, 2007; RS Means, 2006).

The LCC analysis was performed using the free software BLCC5.3 (US DOE, n.d.). This software provides templates ensuring the data entered for each alternative is consistent. The first costs were taken from the hard bid, \$6,200 for the GFA and \$45,688 for the SRS (the material bid was increased to include installation labor and profit). The use, maintenance, and end-of-life information for each system were taken from the process diagrams and assigned time and dollar values. The expected life for each system was held equal at 20 years, the expected life of the GFA system. To compensate for the longer expected system life of the SRS, 30 years versus 20 for the GFA, a greater salvage value was assigned for the SRS system. The salvage value for the SRS system (25%) was estimated based on information from a regional company that resells this type of system components.

FINDINGS

LCA

The initial impacts by phase and system are shown in Table 1 and Figure 2. The SRS system had higher GWP in both the manufacturing and construction phases while the GFA system was higher in the use phase. The 11.6 metric tons CO_2E ($MTCO_2E$) for the SRS manufacturing phase is 85% of the total impact for that system choice. The 10.6 $MTCO_2E$ for the use/maintenance phase of the GFA is 90% of the total impact for this system. It was these phases that were further analyzed for improvement.

LCC

The LCC was performed using the following parameters: A base date of June 1, 2007 was used with an end-of-year discount convention. The interest rate was a nominal 5%, which includes 1.9% for inflation, a BLCC 5.3 data parameter choice. The study period was 20 years and a salvage value of 25% was used for the SRS system to account for the 10 year difference between the GFA 20 year expected system life and the SRS 30 year expected system life. The results are shown in Table 2. The total present value LCC of the SRS system reflects the salvage value resulting in a lower LCC than the first cost. The gas consumption per year reflects the SRS using no natural gas for heating; the sun is the energy source, the real savings for the SRS system. The assumption that the sun can be used as the sole source for energy is based on system sizing for the specific location, building envelope efficiency, passive solar gain, and average number of days of sunshine. The result is an estimated 1,060,000 ft^3 natural gas savings for the SRS over the life of the systems; a direct potential reduction in CO_2 emissions from not using a GFA system. Note the electric consumption (for heating systems only) is the same for each system type to reflect the energy used to run a blower in the GFA

TABLE 1. Summary of total GWP by heating system choice and life cycle phase.

Life Cycle Phase	GFA $MTCO_2E$ GWP	SRS $MTCO_2E$ GWP	GFA Difference
Manufacturing	1.0	**11.6**	–91%
Construction	0.2	**0.4**	–56%
Use/maintenance	**10.6**	1.6	86%
End of Life	–.–	**–.–**	8%
Total	**11.8**	13.6	–12%

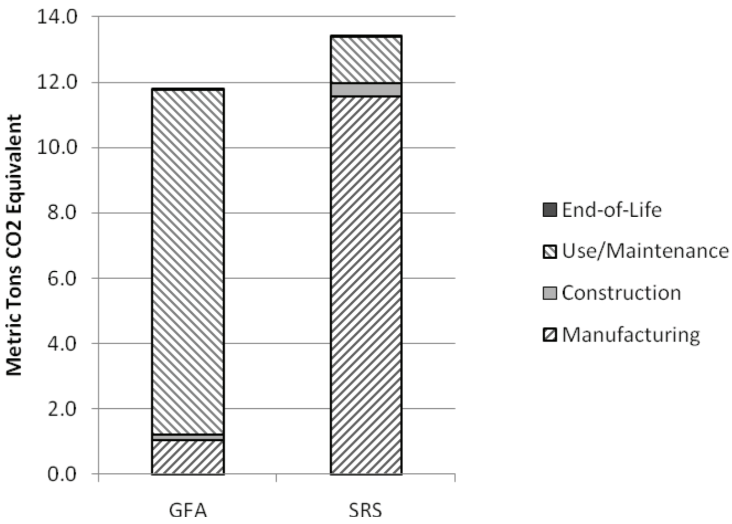

FIGURE 2. Summary of total GWP by heating system choice and life cycle phase.

TABLE 2. Key comparative analysis LCC results for GFA and SRS. (Source: BLCC 5.3.)

	GFA	SRS	GFA Life-cycle Difference
First costs	**$6,200**	$45,688	
Total present value LCC	**$14,795**	$42,278	–$27,483
Average natural gas consumption per year	53,200 ft^3	**0 ft^3**	1,060,000 ft^3
Average system electric consumption per year	3.7MBtu	3.7MBtu	0

system and the pumps in the SRS. This assumption was made due to similar blower and pump voltage, amps, and anticipated run times.

DISCUSSION

The initial findings indicate that the SRS has high GWP in the manufacturing phase and the GFA system has high GWP in the use/maintenance phase. Table 3 shows the comparative CO_2 emissions for each system component for the two systems. CO_2 was isolated for further analysis as the highest single contributing component of all the GWP gasses in the manufacturing phase. The sources of high emissions for the SRS are the solar collectors and the storage tanks, 3.5 and 2.8 $MTCO_2E$ respectively.

TABLE 3. Manufacturing phase CO_2 emissions for both heating systems by NAICS sector.

Material Description	NAICS Sector	GFA CO_2 $MTCO_2E$	SRS CO_2 $MTCO_2E$
Solar FP collector	333414	–.–	**3.5**
Plastic pipe	326122	–.–	0.8
Metal valves	332911	–.–	–.–
Hydronic control	334512	–.–	0.4
Collector stand	332323	–.–	0.4
Transportation	484122	0.1	0.4
Aluminum plates	331316	–.–	0.4
Storage tank	332420	–.–	**2.8**
Expansion tank	332420	–.–	0.1
Pumps	333911	–.–	–.–
Copper tubing	331421	–.–	0.4
Fittings	332913	–.–	0.1
Manifolds/brass	331522	–.–	0.4
Furnace	333415	0.6	–.–
Duct work	332322	0.2	–.–
Floor registers	332323	–.–	–.–
Ceiling registers	332323	–.–	–.–
Return air grill	332323	–.–	–.–
Thermostat	334512	–.–	–.–
Totals		0.9	9.8

Table 4 shows the CO_2 and CH_4 emissions for the use and maintenance phase for both systems; these gasses were isolated for further analysis as the two highest contributors to the GWP in the use/

TABLE 4. Use/maintenance phase CO_2 and CH_4 emissions for both heating systems by NAICS sector.

Material Description	NAICS Sector	GFA CO_2 $MTCO_2E$	SRS CO_2 $MTCO_2E$	GFA CH_4 $MTCO_2E$	SRS CH_4 $MTCO_2E$
Electricity	221122	0.6	0.6	–.–	–.–
NG distribution	221210	**3.3**	–.–	**5.4**	–.–
Maintenance	235110	0.8	0.7	0.1	0.1
Furnace	333415	–.–	–.–	–.–	–.–
Filters	322299	0.2	–.–	–.–	–.–
Pumps	333911	–.–	–.–	–.–	–.–
Antifreeze	325998	–.–	0.1	–.–	–.–
Totals		5.0	**1.5**	5.5	**0.1**

maintenance phase. The GFA emits the most CO_2 and CH_4 in the natural gas distribution category in this phase, 3.3 and 5.4 $MTCO_2E$ respectively.

Using this information, the heating system designers worked to identify possible system component changes to reduce the total greenhouse gas emissions. In this study, the largest contributor of GWP was the manufacturing phase of the SRS. The decision was made to replace the solar collectors with a high-efficiency boiler and eliminate the need for hot water storage tanks in the short run. With the owner's desire to keep the ability to use solar in the future, the system was still pre-plumbed for solar collectors. The data for this hybrid system was entered into eiolca.net and a new analysis was performed. Table 5 shows the results of this hybrid system choice. Compared to the SRS system, GWP in the manufacturing phase dropped significantly however, the GWP in the use/maintenance phase increased due to the need to burn fossil fuels to heat the water. The total emissions for the hybrid system were slightly lower then both of the initial system choices.

TABLE 5. Summary of total GWP by heating system choice and life cycle phase for comparison with new hybrid option.

Life cycle phase	GFA $MTCO_2E$ GWP	SRS $MTCO_2E$ GWP	Hybrid $MTCO_2E$ GWP
Manufacturing	**1.0**	11.6	4.5
Construction	0.2	0.4	**–.–**
Use/maintenance	10.6	**1.4**	6.9
Disposal	–.–	–.–	–.–
Total	11.8	13.4	**11.4**

Energy Use

The energy use of each of the three proposed systems was analyzed for consistency with the GWP findings using 1997 base year data and is shown in Table 6. An interesting note is the GFA used more electricity in the use/maintenance phase than the SRS and the hybrid while the SRS used more total energy than the GFA and the hybrid. The SRS energy use in the manufacturing phase is 104 MJ or 84% of the total impact for this system which is similar to the contribution to GWP of 85%. The GFA energy use in the use phase was 77.0 MJ or 87% of the total system impact; similar to the 90% contribution to GWP.

The LCC analysis results for the hybrid system are shown in Table 7 with a comparison to the GFA and SRS systems. The total present value LCC for the SRS and hybrid systems are still higher than the GFA system. This differential may not be an obstacle in housing markets where the buyer's environmental values support the SRS price premium. While the natural gas consumption increases and the savings from the solar use disappear, the overall LCC indicates that the proposed hybrid system may be a viable choice to heat this new residential home.

CONCLUSION

The initial findings of the LCA and LCC study of the SRS and GFA systems are contrary to the assumption that solar is "green" and sustainable. However, these findings are for two heating system choices in a defined location and were analyzed to determine if improvements could be made in the heating system to lower GWP emissions and/or LCC while meeting

TABLE 6. Comparison of system energy use for phases with greatest difference.

Phase	Total GFA Total MJ	Total SRS Total MJ	Total Hybrid Total MJ	Electricity GFA Electric MkWh	Electricity SRS Electric MkWh	Electricity Hybrid Electric MkWh
Manufacturing	11.6	104	52.5	0.72	6.32	3.64
Construction		–.–	–.–	–.–	–.–	–.–
Use/maintenance	77.0	20.0	53.5	2.06	0.34	1.78
End of life		–.–	–.–	–.–	–.–	–.–
Totals	88.6	124	106	2.77	6.66	5.42

TABLE 7. Key comparative analysis LCC results for GFA, SRS, and hybrid. (Source: BLCC 5.3-07.)

	GFA	SRS	Hybrid	GFA Life Cycle Difference
First costs	**$6,200**	$45,688	$20,489	
Total present value LCC	**$14,795**	$42,278	$23,559	–$8,764
Average natural gas consumption per year	53,200 ft^3	**0 ft^3**	53,200 ft^3	1,060,000 ft^3
Average electric consumption per year	3.7MBtu	3.7MBtu	3.7MBtu	0

the owner's desire for a radiant heating system. The data gathered from the LCC and LCA portions of this study helped the heating design team isolate the components of the two systems that contributed the greatest to either costs or environmental impacts; in this case they were the same. This isolation helped the design team perform an improvement analysis which resulted in the hybrid system where the solar collectors and hot water storage tanks were replaced with a high-efficiency gas fired boiler. While this hybrid system did have the lowest estimated GWP as shown in Table 5, the costs were still significantly higher than the GFA system as shown in Table 7. In this case, the owners felt the market would support the additional expense of the hybrid system.

The use of these tools is important in balancing the owner's needs, environmental impacts, and cost in the design of any system in a residence. In most geographic regions there are multiple heating system choices. The type of fuel and power sources available by region can also differ to a point where the LCC and LCA results for this system may be very different. The viability of the SRS could be determined by looking at what the cost of natural gas would need to be to make the total present value of all life cycle costs for this system a viable option to the GFA or hybrid systems. This type of analysis may become more important based on market conditions, political events, and the volatility these unknowns bring to the energy sector of the world-wide economies.

As this study shows, if LCC and LCA are used properly in the design stage of construction, a balance between cost and emissions can be achieved over the life cycle of the home and its constituent systems. The question of "what does it cost to install?" should be replaced with the question "what can be done to minimize costs and environmental impacts over the life cycle of a system?"

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