COMPARISON OF LIFE-CYCLE ENERGY OF WATER STORAGE TANKS

By

GABRIEL J. EVERHART

A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN
BUILDING CONSTRUCTION

UNIVERSITY OF FLORIDA

2010

To my loving wife

ACKNOWLEDGEMENTS

Many individuals contributed to this report and I thank them all, but no one suffered more than my beautiful wife, Amanda. Without her substantial support, I could not have completed this research project nor in fact could I have enrolled in this graduate program at The University of Florida at all. I would also like to thank my committee members for their time and effort in reviewing this project.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Abstract of Thesis Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Master of Science in Building Construction

COMPARISON OF LIFE-CYCLE ENERGY OF WATER STORAGE TANKS

By

Gabriel J. Everhart

December 2010

Chair: Charles Kibert
Co-Chair: Robert Ries
Major: Building Construction

Currently there is no academic literature available which provides ground storage water tank designers and policy-makers with an understanding of how much energy is required for the construction, maintenance, and final disposal of these structures. This report analyzes three of the most common ground water storage tank designs used in the United States today, over a 50-year life-cycle: (A) prestressed concrete; (B) cast-in-place concrete and; (C) welded steel, and provides an analysis of all energy inputs involved in these structures. Identical dimensions / volumes were used for each tank (1.5 million gallons). The major systems reviewed are embodied energy of materials, transportation of all materials to and from the site, and energy used during construction, maintenance, and demolition. Data sources used include academic literature for energy density values and industry specialists in tank design and construction for construction techniques and technical details. The latter group includes tank designers, tank contractors, demolition contractors, and water plant operators. The final results (in GJ/1.5 million gallons) are: (A) 2,704 (B) 2,392 and, (C) 2,676.

CHAPTER 1
INTRODUCTION

Background

Infrastructure development in the United States continues to increase each year as the population grows and older infrastructure systems are replaced with newer designs. There are over 25,000 water storage tanks in service throughout the United States, connected by over a million miles of water pipe, and totaling many millions of gallons of storage capacity (Environmental Protection Agency 2007). More come on line each week. These installations range from single small, hilltop-mounted ground storage tanks designed to service newly built subdivisions to large, multi-tank wastewater facilities. Storage tanks can be separated into several types, as determined by the materials used in their fabrication. These tanks have historically consisted of either steel or concrete as primary materials. Within these two broad categories are sub-groups of tanks structures which may alter the material composition of the tanks. Examples include welded steel, bolted steel, glass-lined steel, cast-in-place concrete, and pre-stressed, wire-wound concrete, each type with its own expected lifespan and maintenance intervals. Primary materials used are steel and/or concrete, however a variety of materials are in fact used in the construction of these tanks. For example, though mainly consisting of concrete, a pre-stressed concrete tank is actually a composite of materials including mild steel reinforcement, stainless steel, aluminum, fiberglass, plastic, neoprene, and various epoxies and coatings. In addition to the materials which become a permanent part of the tank, there are materials used during tank construction which do not become a permanent tank feature, such as formwork and scaffolding. Some of these materials can be cleaned up and re-used, while others are single-use. Additionally, the construction of a storage tank involves the use of a certain amount of freight transport and equipment (earthmoving equipment, concrete pumps, front end loaders, air compressors, welding rigs, etc), all of which require the consumption of fuels to operate.

Statement of the Problem

Every week in the United States water tank designers are commissioned to produce a tank design for a utility district somewhere. At the present time, little research exists on the life-cycle energy content of infrastructure in the United States, and even less on water storage tanks in particular. Currently, tank designers must weigh tank designs against a large number of competing needs: cost (first and operating), contractor expertise, construction schedule, and maintenance requirements are just some of the many issues which must be considered. Since most utility districts are organized as for-profit enterprises, the addition of a new water storage tank is usually regarded as an investment intended to expand the district's capacity to provide additional product, and earn additional revenue for shareholders. Therefore the return-on-investment calculation is a critical part of the designer's decision. However, as sustainability in construction develops more and more from buzzword to operational goal, tank designers (indeed all designers) and facility owners are beginning to ask more and more questions regarding the relative sustainability impacts of their products. There is a great deal of research and product development concerning the reduction of operational energy use of buildings, but infrastructure projects represent a different sort of problem. With some notable exceptions, most infrastructure projects (roads, utilities, canals, railways, etc.) do not consume a great deal of ongoing energy for operation. Even a conventional building may consume several years' worth of operating energy in its embodied energy during construction (see Table 1-1). When the project in question does not require any, or very little, energy for its long-term operation, other energy inputs are of even greater importance in the overall calculation. It is possible that the embodied energy of an infrastructure project represents the majority of the project's energy consumption over its lifetime. However, what is not known is to what extent this may (or may not) be true for ground storage water tanks. It is not known to what extent the use of tanks of different materials may affect the final outcome of this calculation. The comparative life-cycle energy of water tank types has not been analyzed up to the present time. Designers must make uninformed decisions about which tanks represent the best value in terms of life-cycle energy consumption. Therefore a review of the life-cycle energy of ground storage water tanks makes sense to the designer attempting to achieve sustainability goals on infrastructure projects.

Significance of the Study

The goal of this study is to provide a determination of the complete life-cycle energy over the life-cycle of various types of water storage tanks, per gallon of storage capacity installed, intended to normalize the results against differing tank sizes. The study shall range from initial construction through disposal. The results of the study will allow designers to make more educated choices about which type of water storage tank should be specified. Also the results of the study will provide another metric for tank designers to use in developing new tank designs, as principals of sustainability become more widespread and the tools used to achieve the goals of sustainability become more sophisticated. Although life-cycle energy does not provide the designer with everything the designer needs to know to make a fully-informed design choice, it may serve as a starting point for the design of a more sustainable infrastructure. As future tank designs are developed and refined, it is hoped this study will provide both hard data to use for analysis of different tank options as well as a methodology for future follow-up studies, inevitably to be required in response to changing technologies and methods of construction. Particularly as the world production of oil and coal reaches its peak, and energy prices begin to rise precipitously as expected, a focus on all forms of energy use reduction will have an inherent monetary value in addition to its value as a means to reduce carbon emissions. This will be even more true if the United States ever initiates a carbon tax as expected in some circles.

Limitations of the Study

This study should not be regarded as a comprehensive analysis of the environmental impacts of water tank construction. Life-cycle energy is only one aspect of overall environmental impact, and should be understood as such. It is entirely possible for the extraction of some materials to result in large environmental impacts, but with relatively low embodied energy use (for example, when harvesting pristine forest for wood products). The reverse may also be true. Additionally, a metric which concerns itself with the measurement of energy consumption is unrelated to the method with which that energy was produced; i.e. which fuel may have been used. Naturally the consumption of some fuels produce higher levels of emissions than do others. This study does not attempt to define those distinctions, and is concerned strictly with absolute energy use no matter which fuel is used.

Another limitation is that real-world tank construction methods are somewhat proprietary, and as such are difficult to analyze in some cases due to a lack of available information. There is a dearth of published information regarding detailed water tank structure, erection, and disposal methods. As a result, during the course of this study the author has found it necessary to make certain assumptions and estimates in lieu of actual measurements, particularly regarding the maintenance intervals, life-span and final disposal of some tank types. These estimates have been made after reviewing all available published literature, and supplemented with personal communications with industry contacts such as tank contractors, tank designers, and tank facilities operators located mainly in Florida and Alabama. It is the belief of this author that the final study results are as accurate and comprehensive of real-world water tank construction in the United States as is possible.

Table 1-1. Ratio of lifecycle operational energy to embodied energy*

	Range	Non-Efficient	Efficient
House	Upper	5.8:1	3.6:1
	Lower	10.8:1	5.1:1
Office	Upper	10:01	1.5:1
	Lower	8:01	2:01

(Source: Best and De Valence 2002, P. 80)

CHAPTER 2
LITERATURE REVIEW

Introduction

This report will focus on the life-cycle energy of water storage tanks. The water tank industry in the United States is fragmentary and proprietary, leading to a lack of available centralized, comprehensive information regarding construction materials and methods. A review of the available academic literature revealed no previous studies specifically regarding the life-cycle energy of water tanks, or of the extents of the water tank inventory in the United States. There is some information on the US tank inventory scattered throughout various trade journals and government reports. However, as water tanks do not need to be registered or certified by any government agency the overall US inventory is unknown. Some government studies exist which provide surveys in certain geographical areas. By contrast, there is a great deal of academic literature available regarding the embodied energy of concrete and steel, the primary materials used in modern water tank construction. There have been a number of studies done regarding the life-cycle energy of specific types of structures, in various climate conditions, and comparing various building elements (building envelope, HVAC systems, roofing systemes, etc). In general these studies tend to confirm a pattern of energy consumption of which the greater part lies with the operational phase of a building's life, while the construction phase, embodied energy phase, and demolition phases are all much less significant.

Life-Cycle Energy

Life-cycle energy is defined as "...the embodied energy invested in the extraction, manufacture, transport, and installation of its products and materials, plus the operational energy needed to run the building over its lifetime." (Kibert 2008). Embodied energy is defined as the sum of all energy inputs required to produce a certain material (Malin 1993, May). Most of the attention on building energy consumption in the literature has been focused on the importance of reducing the energy of operating buildings, which is appropriate since building operation accounts for the greater part of overall energy use in buildings (Sartori and Hestnes 2006). As principles of sustainable building science become more sophisticated, however, it is appropriate to look more closely at the embodied energy of various building classes. There is a range in the literature, however, as to precisely what proportion of the that energy consumption is attributable to the embodied energy of the materials and construction process, and which is attributable to energy consumption and end-of-life disposal. For example, Michael Optis and Peter Wild (2010) found that within 20 published studies regarding life-cycle energy consumption of buildings, operational energy ranged between 49 and 92 percent of total life cycle energy. These differences, it was found, were due mainly to different choices made in where to define the boundary of the system studied and which data sources are used. As the energy used to complete a finished product is derived from a large network of increasingly indirect sources, it is important to clarify what the boundaries will be. The system boundaries of this study are defined in the next chapter. A 2006 study by Sartori and Hestnes found that among low-energy buildings, the construction, transportation, and demolition phases account for only 1% or less of the building's total energy consumption, while the embodied energy of materials account for anywhere from a third to a virtually negligible amount of the total.

Of course a water tank is not a building in the normal sense. The actual "operation" of a water tank, using the term loosely, is primarily in the form of the pumps required to fill the tank. The water exits the tank generally though gravity into a network of pipes which service the public, assisted as necessary via a network of booster pumps built into the system at strategic locations. None of this equipment is typically located within the tank itself, but rather at a remote location down- or up-stream. Occasionally some electronic valves may be included in the piping system for remote flow control, with the possible additional of low-voltage sensors for data collection on water pressure, level, temperature an so on. For this reason the proportion of energy used for the operational phase of life-cycle energy consumption is much smaller than for a conventional building, and the proportion of energy which is derived from the embodied energy of materials is of much greater importance. Keoleian et al. (2000) made a similar finding, determining that energy-efficient structures typically contain as much as 26% of their life-cycle energy consumption in their embodied energy.

Materials selected during design can have a large impact on the embodied energy of a structure. A New Zealand study (Buchanan and Honey 1994) found that there was a potential for significant savings in embodied energy and carbon emissions if material use was shifted from concrete, steel, and aluminum to more sustainable wood products. It was noted that this shift would have a greater impact on forestry resources, however.

Generally, embodied energy can be classified in to first, second or third order energy use. Nadav Malin (May 1993) in Environmental Building News uses the following definitions:

1. First order: energy used for the raw extraction/harvesting and processing of materials. Includes transportation from site of extraction or harvesting to any and all further processing locations.

2. Second order: energy used in the manufacturing of the equipment used to extract or harvest the raw materials, as well as any equipment used to process or fabricate the initial material or product. This category also includes the energy used to transport workers to and from the site of construction.

3. Third order: energy used to provide support services for workers, and to maintain the infrastructure required to support construction activities (roads, utilities, etc...).

Most studies of embodied energy focus primarily on first order energy inputs. It is the intention of this report is to follow a similar strategy.

Scheuer, Keoleian and Reppe (2003) conducted a life-cycle energy study and environmental assessment of a new mixed-use building at the University of Michigan. Among their findings were that the building's overall life-cycle energy consumption was 3,401 GJ/sf. However the proportion of the energy consumption from the embodied energy of the building, including material transportation, and building disposal was only 2.4%. All other energy use was attributable to building operation over a 75 year study period. The embodied energy consumption was 51,000,000 MJ, or 2.05 MJ/sf.The three mateirals which contributed the most to the embodied energy of the building were steel, cement, and sand, mainly due to the their presence in large quantities within the building structure. The study did attempt to include the effect of construction worker transportation by adding in a value equal to 5% of embodied energy, consistent with previous studies by Cole and Rousseau (1992), which found that worker transportation energy use falls typically in the range of 6.5 to 10% of embodied energy totals.

In the study it was also noted that energy use impacts of upstream facilities, such as plants and mills and factories, was "relatively insignificant."

CHAPTER 3
METHODOLOGY

System Boundaries

This study will focus on providing a comparison of the life-cycle energy consumption of three different water-storage tank designs. The three different tank designs selected for the study represent the majority of all ground-storage water vessels built by municipalities in the United States today (Environmental Protection Agency 2007). Tanks not included in the study were fiberglass, glass-lined steel, and reservoir systems, as these represent a much smaller percentage of the overall inventory of tanks in use at the time of this writing. The tanks selected for study are:

- 1. Concrete, prestressed (wire-wound)
- 2. Concrete, cast-in-place
- 3. Steel, welded, painted

Other tank options which are not included in this study are glass-lined welded steel, fiberglass (smaller tanks), bolted steel, and open basins. These were excluded from the study primarily because these tank types are not widely used in the industry (Environmental Protection Agency 2007), and secondarily because information on embodied energy and construction methods were not readily available. In the case of bolted steel tanks, there is not much difference between bolted and welded, and this author determined it was unnecessary to include both. The study period is 50 years, chosen because this period is considered within the tank industry to be a fairly average lifespan for a well-maintained tank. In order to make accurate comparisons across system types, tanks with similar volumes, dimensions and accessory items have been selected for comparison. The selected tanks will have a volume of approximately 1.5 million gallons (typical of a medium-sized storage tank) and dimensions of 85 feet in diameter and 35 feet in height (to the high water level). The functional unit shall be in MJ per 1.5 million gallons of water storage capacity. It is assumed the tanks will include a standard set of accessory items including a level-indicator, a ground-level hatch for construction access, a dome-mounted hatch for access during operation, and both an exterior and interior aluminum ladder to access the dome hatch. There are several other types of appurtenances which may be added to any type of tank (fiberglass top-side vents, concrete sumps, baffle walls, aluminum ladder cages, stainless steel mixing systems, copper lighting protection systems, etc) but any of these items may be added virtually as is (with little design change to the accessory) to any type of tank, thereby making a comparison between tank types unnecessary. Whether a fiberglass overflow vent is added to a steel tank or a concrete tank, it does not affect the inherent life-cycle energy value embodied into steel and concrete tanks; therefore its effect is not included in this study. Additionally, although tanks are sometimes painted for aesthetic reasons, for the purposes of this study no unnecessary paint coatings are included. This excludes the case of the steel tank design where the coating system is an integral part of the design intended to prevent corrosion, and its absence would drastically affect the tank life-span. The plans and specifications used for review in this study were procured directly by the author either from a tank manufacturer, tank designer, or plant operator. Figure 3-1 shows categories of energy use included within the boundary of the system studied, and what items were omitted.

Embodied Energy

The value of the embodied energy of materials were gathered using various sources. Lumber and plywood values were obtained from Keoleian et al. (2000). Values for concrete ingredients came from Worrell at el. (2001). All other material values came from The Inventory of Carbon and Energy (ICE) database version 1.6a, Sustainable Energy Research Team (SERT), produced and updated by the University of Bath.

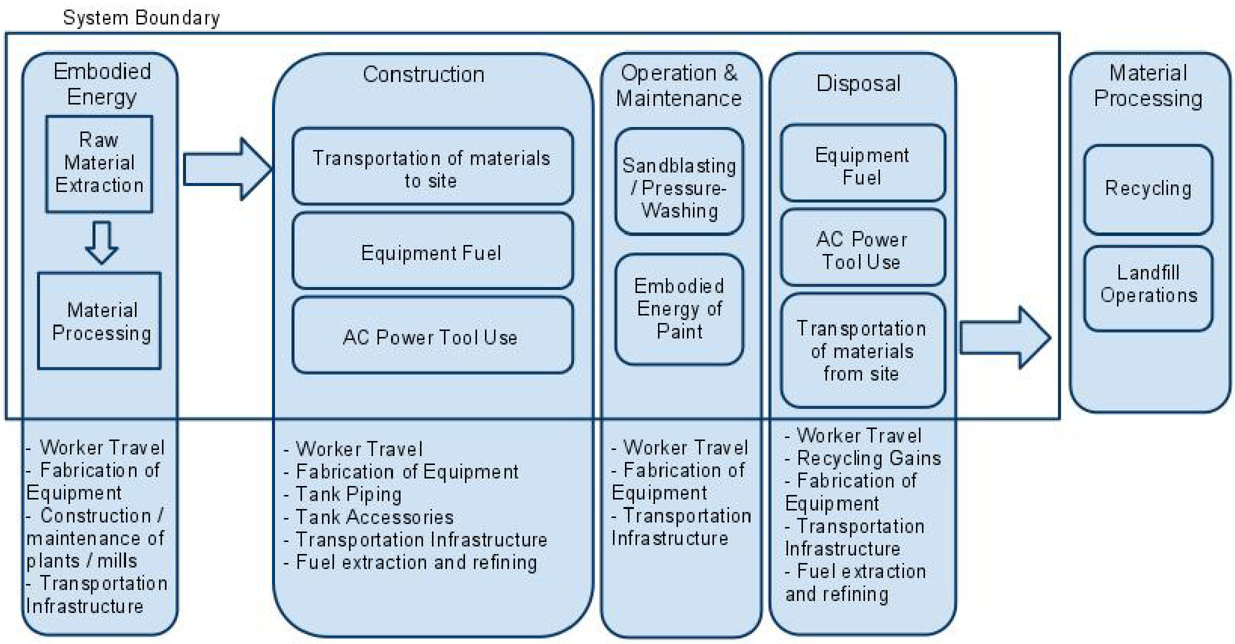

Figure 3-1. System boundary of the study

The embodied energy values given in these reports are given as cradle-to-gate; that is, the full energy value of extracting raw materials, transporting those materials to another location for further processing, and then also the processing energy consumed at that second location. Cradle-to-gate methodology has become the norm in LCA analysis, and as a result the values across multiple studies are easier to compare. Therefore, no further transportation energy is included in the "embodied energy" category for, as the ICE authors state, "It is now encouraged for the user to consider the impacts of transportation for their specific case." Feedstock energy, or the fuel-energy value of materials used in material processing, is included in the embodied energy values.

The quantity estimates of the final, in-place materials in the tank have been increased by an efficiency / waste factor as given below, except in the case of the prestressed concrete tank.

- 5% Concrete
- 5% Metals
- 8% Lumber and Plywood
- 3% Plastics and misc

These percentages represent both the estimated losses encountered in processing the raw materials into finished products and construction waste on site. These percentages represent a slight difference from Keoleian et al. (2000) which used a straight 5% waster factor for all materials; however it is the opinion of this author that these percentages more accurately reflect real-world wastage circumstances. The mass of materials for the prestressed concrete tank were obtained directly from the bill of materials as actually ordered by the tank manufacturer, and therefore the internal company's waste factor was already applied to those quantities. Formwork lumber is a special case, where the material may be reused several times with some loss of material each time due to damage and the inconvenient geometry of small pieces which are discarded after a single use. After consulting directly with tank contractors it was estimated that this material could be used up to 4 times for formwork, with a 10% loss of material each time. The shoring / scaffolding used to support the dome formwork in the case of the prestressed concrete tank were not included in the study as that was considered to fall under the category of "fabrication of equipment," which was omitted from the system boundary of the study. When shoring / scaffolding manufacturing was included in the study, conservatively assuming a re-use rate of 40 uses before being discarded, an additional 13,000 MJ was added to the study results, or an increase of just 0.48 to 0.54%, depending on the tank. Admittedly the reuse rate of 40 uses is a rough estimate by the study author, however it is clear that halving - or doubling - this rate would have a negligible effect on the study results. Likewise, note that conflicting values for the embodied energy of some materials were encountered, however in these cases it was found that the difference did not contribute significantly to the final resulting comparison between tanks.

Construction

This stage includes all energy consumption related to the act of actually erecting the tank. This category would involve three main subcategories, namely transportation of construction materials to the site, fuels from heavy construction equipment used (front-end loaders, concrete pumps, heavy generators, etc), and the direct use of AC power by small hand tools such as drills and circular saws. For transportation, the total quantity of materials and equipment was estimated (minus concrete and steel, to be handled separately) and converted to a total number of standard tractor trailer truckloads. This was then multiplied by an assumed distance of 300 miles from the tank contractor's base of operations, divided by an average of 7 miles per gallon for a fully loaded truck. In addition to this the number of truckloads of concrete was estimated based on 9 cubic yards per truck, an assumed distance of 20 miles to the nearest batch plant, and again using 7 mpg for the concrete trucks. For the steel reinforcement it was assumed this material would be shipped directly to the site from the fabrication facility, which was assumed to be 100 miles away. Based on personal communications with industry contractors, a tractor trailer is generally loaded safely to carry a maximum 38,000 pounds of material. Therefore the total of the steel reinforcement was divided by this weight limit to get the number of trucks required for the steel delivery; again it was assumed the trucks would be traveling at 7 mpg.

The exact mix of heavy equipment used for construction varied for each of the three tank types. A list of each piece of equipment required for each tank type was made, and a calculation of the total fuel consumed in this category was made by multiplying the estimated number of hours of operation per day for each item multiplied by days in the project, multiplied by an average rate of fuel consumption for each item. All equipment was assumed to be diesel-powered.

Also included in this category of power use is the small hand tools used during the construction process, such as drills, saws, grinders, and so forth. These tools are mostly corded, though a few, mainly drills, may be cordless. The total kWh of energy consumption for power tools was calculated by multiplying 90% of the estimated days of construction by an assumed average number of hours of operation per day (inclusive of all power tools together) multiplied by an estimated average wattage of 1500 watts per tool. This would be typical of a tool running on 120 volts at 10.5 amps, an average number. Ninety percent of construction days were used in lieu of 100% as it was assumed there would be days, particularly during job setup and shut down, when tool use would be limited.

Operation and Maintenance

An assumed life-span of 50 years for each tank type was determined through interviews with industry contacts and publicly available information. The operational energy of a water storage tank is fairly low compared to other structures, and energy-consuming items used for one type of tank can typically be used for all types, i.e. the use of remote sensors for water level monitoring, electronic valves to fill or empty the tank, security lights and cameras, etc. These items are generally included in the tank design regardless of tank type, depending on the needs of the owner and the predilections of the designer. As it is arguable that these items do not actually count as "operation" of the tank itself, and because these items may be included into any tank design regardless of type, they were excluded from the study results on the basis that they would not affect the final comparisons.

The energy consumption of the maintenance of the tanks over the 50 year study period was calculated differently for the different tank types, though essentially the process was similar. An assumed maintenance schedule was determined for each tank type and the required equipment and materials necessary for the completion of that schedule was estimated. The embodied energy of any materials was determined using the same method used for the initial construction of the tank. Equipment fuel use was calculated by estimating the number of hours operation for each piece of equipment multiplied by an estimated rate of fuel consumption per hour. Table 3-1 shows the schedule of maintenance operations assumed for each tank type.

Table 3-1. Scheduled maintenance operations by tank

Tank Type	Frequency
Concrete Tank [cast-in-place]	
Pressure wash exterior	every 5 years
Concrete Tank [prestressed]	
Pressure wash exterior	every 5 years
Steel Tank [welded]	
Pressure wash exterior	every 10 years*
Sandblast and re-paint interior / exterior	every 10 years*

**Alternating every 5 years*

Disposal

The process of dismantling and disposing of each tank type was determined through interviews with demolition contractors, and the energy required to complete that process at the end of its operational life was estimated. This calculation includes the fuels used by demolition equipment and the transportation of the materials to either a landfill or recycling center. The recovery of materials via recycling was not included in the calculation under the rationale that that recovery, although undeniably beneficial to society at large from a material resource point of view, would not affect the outcome of the inherent life-cycle energy consumption of the tank from the Owner's point of view. The EPA's "Second Allocation Method" proposes that the effect of recycled materials of embodied energy be allocated to the system which next uses those materials Vigon et al. (1993). Most of the steel from a water tank is generally recycled, even the reinforcement embedded in concrete. In this case the concrete would be mechanically agitated, or crushed, until it is separated from the steel and then steel and concrete both can then be further processed separately.

Data on equipment, time, and materials required to demolish a tank was collected directly from interviews with demolition contractors with experience in tank removal. An estimate of equipment hours and fuel usage rates was made for each tank type, and the resulting energy consumption was calculated. An estimate of power tool use was also made. This category also included the transportation energy to bring the demolition contractor's equipment to and from the site (assuming an average distance of 100 miles) and to remove materials from the site (assuming an average distance of 30 miles to the nearest landfill or recycling center). As in the calculations for construction, it was assumed power tools would operate at an average power rating of 1500 watts (120 volts x 10.5 amps) and that standard tractor trailer trucks would be used for all transportation, with an average load of no more than 38,000 pounds.

Omissions

The most comprehensive energy-use analysis of any product would ideally include all upstream uses of energy, in addition to energy use after the product is disposed of. However as has been stated in previous studies (Scheuer et al. 2003), beyond a certain upstream level the impact of associated processes become unimportant. The systems and materials which were not included within the study boundary were as follows:

1. The fabrication and maintenance of construction equipment and miscellaneous tools.
2. The construction and maintenance of factories, fabrication plants, or mills.
3. The effect of site work preparation. As this is highly variable depending on local conditions and does not change from one tank type to another, it was decided to exclude these effects from the study results.
4. Elevated tanks and underground tanks. Generally a tank designer has a specific need for one type of tank or another, and does not need to consider whether to design for an elevated tank, ground storage tank, or buried tank. The logical alternative for comparison for an elevated tank, for example, would be a system of pump stations; not another kind of tank.
5. Piping inside or under the tank.

6. Any transportation or utility infrastructure generally required for construction (roads, water piping, electrical grid, etc).

7. Energy saved by recycling materials at the end of the tank lifespan.

8. Miscellaneous tank accessories such as ladders, hatches, level indicators, etc. The mass of these items are quite small compared to the overall mass of the primary tank materials, and as in site work these items can be included on any kind of tank and therefore no benefit is gained by including them into the comparison.

9. Miscellaneous site features which often, but not always, accompany the construction of a new tank such as security fencing, cameras, site lighting, etc.

10. Miscellaneous items and systems used by construction crews during construction, such as personal protective equipement, paper products, bathroom facilities, signage, etc.

11. Overhead burden resulting from the operation of the offices of the tank contractor, designer, or owner.

12. The impact of worker travel, including workers at the construction site, fabrication plants, etc.

13. Impact of raw material extraction and refining of fuels.

Upon review of the available literature it is expected that the omission of these items will have no great impact on the overall result of the comparison study presented here. These omissions are among those commonly made in most life-cycle energy studies.

Tank Descriptions

This section will describe the construction details of each tank type. Generally, a site must be cleared and graded as preparation for the construction of a tank. Usually it is necessary to over-excavate and import engineered fill material, compacted to meet the requirements of the geotechnical engineer. Stone is usually used as part of the subgrade base material to allow for proper drainage. This is true of all tanks, regardless of construction materials used. Additionally the exact amount of over-excavation and compacted fill and stone used varies considerably from site to site, depending on local conditions. For these reasons energy consumption related to sitework preparation are left out of the study.

Concrete, cast-in-place: Cast-in-place structures are widely used in construction, and perhaps because of this familiarity this method is common in tank construction as well; the knowledge of how to build a cast-in-place structure is well-known by contractors. The general process is similar to the construction of a cast-in-place building. After the subgrade is prepared heavy gauge plastic sheathing is spread out to cover the area of the tank footprint. Steel bolsters are placed on the plastic sheathing, and then steel reinforcement is placed on the bolsters. There will be another layer of bolsters and reinforcement, which make up the top mat of reinforcement, which generally cross each other orthogonally. The formwork, consisting of 3/4" plywood reinforced with 2x lumber, is then placed around the perimeter of the tank slab in preparation for pouring the tank slab. The slab in this design is typically 12 inches thick, with concrete strengths of 4500 psi. After the slab is poured, a flexible rubber and clay waterstop is placed at the tank floor-wall joint, and plywood formwork is built up from the slab surface to create the first lift of the tank wall pour. The tank walls are typically 12 inches thick, poured in lifts that are typically no more than 10 feet in height. Once each lift is poured, additional reinforcing is placed in the next wall section, additional plywood forming is placed, and that lift is then ready for casting. For the purposes of this study it is assumed the tank walls will require three lifts. Once the walls have been completely cast, an aluminum dome is assembled on the ground and swung into place with a truck-mounted crane (figure 3-2). The dome is assembled with interlocking triangular panels bolted in place over an aluminum girder framework (TEMOR Industrial Products 2010). Concrete tanks do not require any regularly scheduled maintenance regimen for their continued operation, however it is quite common for the Owner to have the tank pressure-washed occasionally for aesthetic reasons, particularly in humid climates where mold and mildew discolorations on the tank exterior can occur.

Figure 3-2. Aluminum dome lifted into place. (Source: TEMCOR Industrial Products)

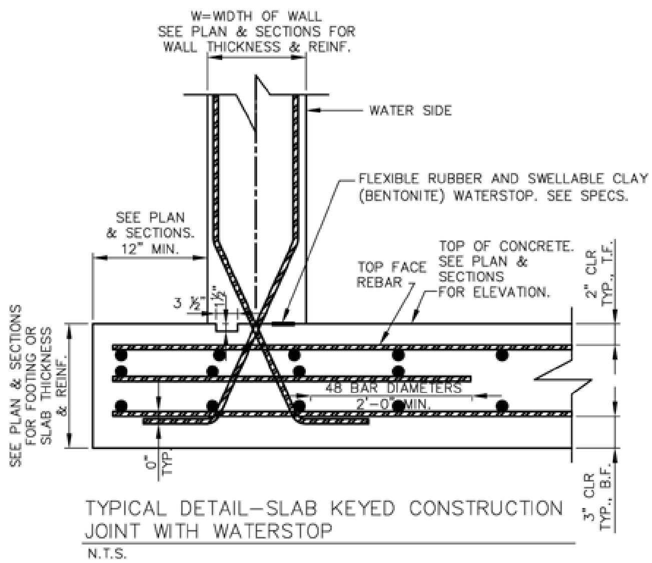

Figure 3-3**.** Cast-in-place water tank section. (Source: Holmberg, July 2009)

Concrete, prestressed (wire-wound): This type of storage system is actually a composite of materials, mainly concrete and steel, erected in layers. In this type of tank design the slab is constructed in much the same manner as for a cast-in-place concrete tank. After the site is prepared a plastic sheet is laid down over the slab area, steel bolsters and reinforcement are placed, and a lumber form is built around the perimeter in preparation for the slab to be poured. A polyvinylchloride waterstop at the floor-wall joint is suspended from the formwork so that it will be partially embedded into the slab. The slab is then poured with 4500 psi concrete using a concrete pump with a boom extension. Once the slab is poured the dome shoring is erected in rings, starting in the center of the tank and working outwards. When the final outer ring of shoring is in place a ring of 26 gauge sheet metal diaphragm is hung from the outer ring of shoring, each piece lapped to the one next to it and the two pieces crimped together. The diaphragm is hung so that its bottom edge is held within a groove in the waterstop, into which a waterproof epoxy is then poured. The diaphragm and waterstop are now sealed together into a water tight barrier. A small-scale concrete pump and air compressor are then used together to build up concrete on the outside surface of the diaphragm using a process called shotcreting, which is essentially the spraying of concrete. This step also uses 4500 psi concrete. The shotcrete process is accomplished using a rolling steel scaffold powered either with compressed air or a diesel engine. As the wall builds in thickness, intermediate layers of #4 or #5 steel reinforcement are placed vertically in the wall at various intervals. Once the outer layers of shotcrete have been placed at the designed final thickness (typically 5-8 inches) the rolling scaffold is moved inside the tank using a truck-mounted crane and a thin (1 inch) layer of shotcrete is placed on the inner surface of the diaphragm. The rolling scaffold is removed, again via crane, and a plywood formwork is installed supported by the rings of shoring previously placed. The dome is then cast in concrete at 3" thick. Eight gauge steel wire is then wrapped around the exterior of the tank from top to bottom at 3000 psi, and a final 1 inch layer of shotcrete is applied over these wires. Any accessory items are then added, and the tank is ready for use. As previously stated in the cast-in-place tank section, no maintenance is required in a concrete tank other than occasional pressure-washing as needed at the request of the Owner.

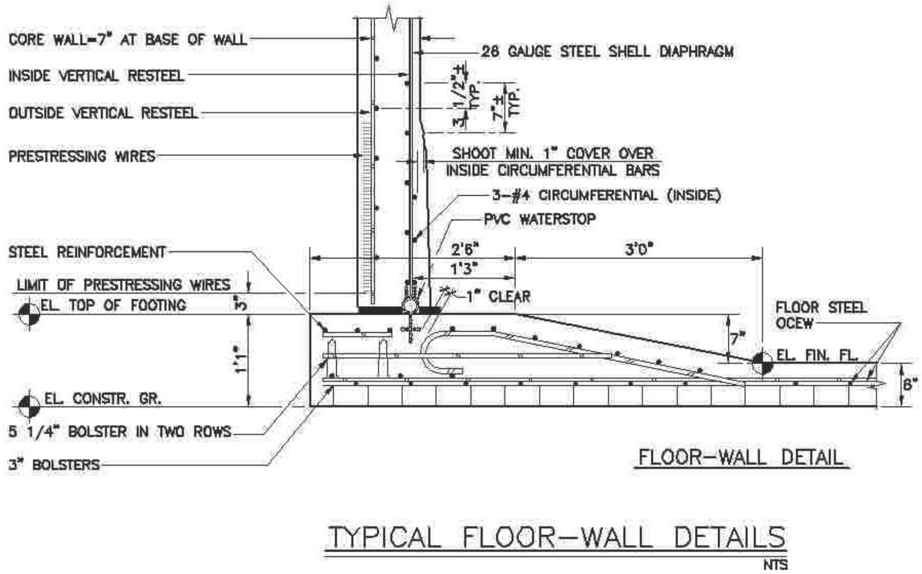

Figure 3-4. Prestressed concrete water tank section. (Source: adapted from personal communications and engineering drawings as acquired from industry contacts.)

Steel, welded: As in other tank designs, this type of tank typically uses a 6" reinforced concrete slab for the bottom surface. A plastic sheet is laid down over the cleared and graded tank area first. Then reinforcement steel is placed on steel bolsters while a form work is built around the perimeter. A concrete slab of 4000 psi is poured with a steel channel placed (embedded) into the outer edge to act as a waterstop and give the steel wall panels a place to be secured. Once the slab has cured sufficiently a portable truck-mounted crane is used to fly 33' x 10' shop-primed steel panels into place for attachment to the embedded channel, this is repeated until the first ring of panels has been places and secured to the tank base. each panel is first tank-welded into place, then a full weld is applied to fully secure the panel. The next ring of steel panels is flown into place and welded on like the first ring, with each ring being self-supporting once it forms a complete circle. The tank walls are placed until the dome level is reached, at which point a series of horizontal box girders are welded into place around the tank on the interior to act as wind bracing. The dome is then secured in rings in a similar method as the walls. Once the tank shell is in place, the entire tank is coated, interior and exterior, with two coats of paint specifically formulated for protecting steel from the corrosive effects of weathering. The accessories can then be installed, and the tank is ready for service. (Todd Huffman – Siemens Water Technologies, personal communication, September 16, 2010.)

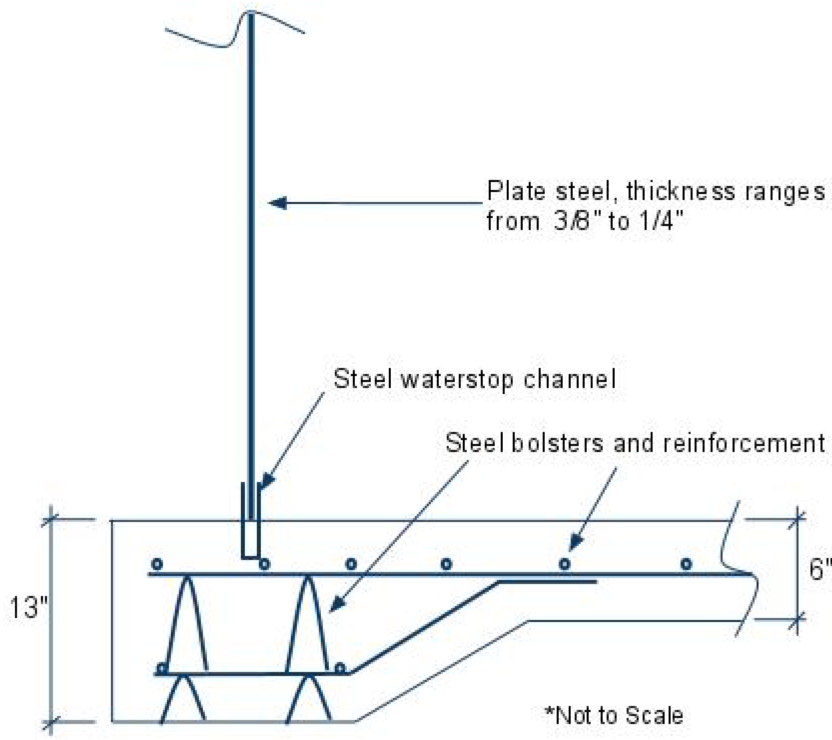

Figure 3-5. Welded steel water tank section. (Source: adapted from personal communications and engineering drawings as acquired from industry contacts.)

CHAPTER 4
RESULTS

Material Inventory

Once a complete quantity takeoff is calculated for each tank it is possible to review the inventories per tank. Table 4-1 provides the kilogram weight of all materials used during tank construction, including temporary materials which would not become a permanent part of the tank, such as formwork lumber. In this case the wood is still consumed for the purpose of tank construction, even though it may be used several times before becoming unusable. This table also demonstrates the value used for the energy density of all materials, for reference. Concrete was broken down into its constituent parts, cement, water, sand, coarse aggregate and flyash (assumed to be replacing 20% of the cement quantity).

Table 4-1. Mass and embodied energy of tank materials

		Kilograms		
Material	MJ/kg	Concrete, Cast in Place	Concrete, Prestressed	Steel, Welded
Sand	0.60	391,148	507,465	56,352
Coarse aggregate (stone)	0.20	662,557	196,417	95,453
Cement	5.40	169,963	175,514	24,486
Steel, plate	13.60	-	-	95,672
Water (in concrete)	0.20	94,793	94,923	13,657
Fly ash	0.05	41,576	37,896	5,990
Steel, bar	8.80	24,056	24,451	9,275
Plywood	8.30	10,731	6,668	-
Steel, wire	36.00	-	8,491	-
Lumber	28.50	5,480	15,664	590
Aluminum	28.80	6,756	-	-
Steel, sheet	13.60	-	3,455	-
Waterproofing epoxy	139.32	-	575	-
Polyvinylchloride	65.20	550	366	-
Plastic, all types	105.30	117	203	117
Synthetic rubber	99.88	-	11	-
Paint[1]	1.90	-	-	na
Total		1,407,727	1,072,097	301,591

[1]*value given is per square foot*

As demonstrated by many sources, this table confirms the relatively high energy density of metals and plastics compared to less processed products like lumber and the ingredients for concrete. The most highly processed products, such as the synthetic rubber and the waterproofing epoxy (a reaction product of epichlorhydrin and bisphenol A) show the highest values for energy density, as expected. The waterproofing epoxy, for example, contains approximately 26 times the energy density of cement. In the final analysis, however, most of the high-energy density materials have a minor impact on the results as they are generally used in much smaller amounts than other materials. For example, on the prestressed concrete tank the four materials of greatest energy density (waterproofing epoxy, polyvinylchloride, plastics, and synthetic rubber) account for only 0.11% of the total building mass, although they account for 4.68% of life-cycle energy. Their energy impact greatly outweighs their relative mass (by roughly a factor of 43); however their actual mass in the building is so limited that their overall impact is still very small.

Energy Inventory

By multiplying the mass of tank materials by their respective energy density per kilogram an analysis can be made of the overall impacts of individual materials, shown in table 4-2. The initial quantities are given in megajoules within the table but the totals are converted to gigajoules (rounded to the nearest whole). This table also includes the impact of processes such as fuels used for construction, transportation, and direct AC power use, which reveals the overall contribution they play in the life-cycle energy consumption of each tank type. These results demonstrate the relatively minor role these processes play in the tanks' life-cycle energy consumption, relative to the energy content of the tank materials.

Table 4-2. Life-cycle energy use of tank materials and processes

	Megajoules		
Material / Process	Concrete, Cast in Place	Concrete, Prestressed	Steel, Welded
Steel, plate	-	-	1,301,133
Paint	-	-	683,218
Cement	917,800	947,773	132,225
Steel, wire	-	249,325	-
Fuels for equipment	241,408	287,501	252,527
Aluminum	194,586	-	-
Sand	234,689	304,479	33,811
Fuels for material transportation	221,417	205,977	139,461
Steel, bar	211,689	215,169	81,622
Lumber	142,116	239,932	16,821
Waterproofing epoxy	-	80,154	-
Coarse aggregate (stone)	132,511	39,283	19,091
Steel, sheet	-	46,992	-
Polyvinylchloride	35,866	23,861	-
Plywood	24,710	18,979	-
Plastic, all types	12,309	21,384	12,309
Water (in concrete)	18,959	18,985	2,731
Fly ash	2,079	1,895	299
Direct AC power use	1,766	999	567
Synthetic rubber	-	1,057	-
Total (GJ)	2,392	2,704	2,676

It is illustrative to look at the ranking of tank materials, separated for each tank, in order of greatest to least energy impact as shown in figures 4-1 to 4-3. This allows a quick understanding of the relative impacts of each material class.

It is worth noting that the two concrete tank types follow similar patterns of energy consumption, or energy profiles; they see some of their greatest consumption in the embodied energy of their cement and steel reinforcement. The plate steel used on the welded steel tank represents a disproportionately large percentage of the energy consumption on that tank design. Also of note is the second-place item on the welded steel tank, paint. Although only a very small fraction of total tank weight, the contribution of paint to the total life-cycle energy of the tank is high because not only because of the inherently higher energy-density of this material relative to other materials, but also because it is necessary to re-apply the paint to the tank at regular maintenance intervals. The rate of re-application of the paint to steel tanks is assumed to be every 10 years in this study, based on an informal survey of recommendations by plant operators in Alabama and the Florida panhandle.

The total life-cycle energy use per tank, per life-cycle stage is shown in Figure. 4-4. The results indicate that the energy consumption of all three tanks fall in relatively the same neighborhood. The cast-in-place concrete tank consumes the least energy over the 50 year study period, with the welded steel tank next and the prestressed concrete tank consuming the most. Figure 4-4 also demonstrates the relative energy density for each life-cycle stage for each tank, showing the very high proportion of energy which is due to the embodied energy of construction materials relative to the construction process, maintenance and disposal stages. The embodied energy of materials stage alone accounts for between 64% to 82% of the total life-cycle energy of tank construction, depending on the tank. As there is very little operating or maintenance energy required of a water tank, this finding is expected.

Comparison of Functional Units

In order to normalized the results the functional unit of a Megajoule per 1.5 million gallons (mg) of water stored is used. The results, shown in table 4-3, show an energy density of 2,392 GJ/1.5 mg for the cast-in-place concrete tank, 2,704 GJ/ 1.5 mg for the prestressed concrete tank, and 2,676 GJ/mg for the welded steel tank. Table 4-3 provides a further breakdown of the energy density of each phase of the life-cycle, as broken down by the four main stages of life-cycle energy: embodied energy of materials, construction processes, maintenance, and end-of-life disposal.

Table 4-3. Energy density per life-cycle stage (GJ)

Life-Cycle Stage	Concrete, Cast in Place		Concrete, Prestressed		Steel, Welded	
Embodied Energy of Materials	1,927	81%	2,209	82%	1,714	64%
Construction Process	293	12%	354	13%	236	9%
Maintenance	41	1.7%	41	1.5%	663	25%
Disposal	130	5%	99	4%	63	2.4%
Total Energy Consumption (GJ)	2,392		2,704		2,676	

The very high proportion of life-cycle energy attributable to the embodied energy of materials and the construction process again reveal themselves in this analysis. A closer look at these results also reveal a disparity from one tank type to another in how the energy use is allocated across life-cycle stages. While the welded steel tank uses 25% (663 GJ) of its energy in its maintenance stage, it uses only 64% (1.714 GJ) of its energy use in its embodied energy of materials category. This is in sharp contract to the values for the other two tank types, which had values of 81% and 82% in the construction category, for cast-in-place and prestressed concrete respectively, but values of only 1.7% and 1.5% for maintenance. A major factor influencing these results is due in large part to the length of schedules estimated for each tank type. Based on interviews with steel tank contractors, the welded steel tank was estimated with the shortest schedule, 10 weeks, for the duration of the project. Because power tool and heavy equipment use are the largest energy factors in the construction category, and these are in turn a direct function of project duration, it is not surprising that the shortest project would consume the least amount construction energy.

In order to simplify the inputs of material mass into the tank designs, figure 4-5 graphically condenses all primary materials for each tank type together, so that all steel products are grouped together under “Steel”, all ingredients for concrete are grouped together under “Concrete”, “Lumber and Plywood” is together, and everything else is grouped together under “All Other Materials.”

The welded steel tank naturally consists mainly of steel (35% of total mass), while the two concrete tank designs show not only much less steel and more concrete, but a corresponding greater amount of lumber required for forming the concrete. The lumber used in formwork can in most cases be reused on another project, with some attrition for each such transfer. For this study it was estimated that plywood and some other select pieces would be salvaged and reused up to 4 times before being discarded, with a corresponding loss of 10% of the whole each time. The welded steel tank also required some lumber to act as formwork for its concrete slab, however in that case the formwork is limited to only what is required to form the edge of the slab perimeter, and therefore its mass is relatively minor. The mass of all other materials is slight in all three tank designs, ranging from 0.04% for the welded steel tank to 0.11% and 0.53% for the prestressed and cast-in-place concrete tanks, respectively. The aluminum dome of the cast-in-place concrete tank is an energy-intensive material which by default has been grouped with "All Other Materials," making that category a much larger percentage of the whole relative to the other two tanks designs. Table 4-4 provides a side-by-side comparison of how the mass of each material compares to its relative contribution to the tank's life-cycle energy consumption.

When compared to the processes required for tank construction, maintenance, and disposal, the tank materials percentage of life-cycle energy use becomes correspondingly smaller. Table 4-4 demonstrates clearly the tremendous difference between the mass of a particular material and its corresponding value in life-cycle energy consumption. For example, the concrete tank designs maintain 94-97% of their mass in concrete, quite naturally; however that same mass of concrete accounts for only 49-55% of the tanks' life-cycle energy consumption.

Transportation Effects

It is also worth noting the effect of transportation miles travelled on the overall energy consumption of the tanks, and performing a basic sensitivity analysis. The transportation category accounted for between 5 to 9% of the total life-cycle energy of these three tanks, with the highest amount of energy expended on material transportation for the concrete tank designs. Based on interviews with tank contractors it was determined each contractor would require a fabrication shop / staging facility for the servicing of its projects. It is at this facility, or shop, that the contractors' equipment is stored and serviced, miscellaneous materials are gathered and allocated to each project, and so forth. The exceptions would be concrete, which would be delivered directly to the site from a local ready-mix batch plant, and steel reinforcement, which would also be delivered directly to the site from a nearby steel plant. It was also assumed that at the end of the tank's service life of 50 years most materials would be disposed of at the nearest recycling facility or landfill. The following assumptions were made regarding distances to the project location: contractor's facility 300 miles; steel plant 100 miles, concrete plant 20 miles, landfill / recycling center 30 miles. As stated previously, an average rate of fuel consumption of 7 miles per gallon is used for the heavy trucks in this analysis, based again on interviews with dispatch operators at contractors' fabrication facilities. A simple spreadsheet model was created to allow an adjustment of these assumptions and analyze the different results. In this fashion it was possible to isolate the amount of energy per mile that each of these inputs contributed to the total, and then determine what percentage of the total that value represented. Table 4-5 below shows the results in both absolute energy and percent of the whole.

The upper set of numbers are, except in the last case, in units of megajoules per mile; for a cast-in-place concrete tank every mile from the contractor's facility adds 418 MJ of energy to the project total. A factor which has a heavy impact on these values is the amount of material being transported in each category; i.e. the distance to the concrete plant has a much greater impact on the concrete tanks than the steel tank, which is proportionately more impacted by the distance to the steel plant. The last item in each section deserves special consideration. The fuel efficiency of the trucks, as measured by each mile-per-gallon difference, has a greater impact than the other categories because it affects all other categories of transportation. It shows, for example, that about ½ to 1% of total life-cycle energy can be reduced from the project for every mile-per-gallon increase in the average fuel efficiency of the vehicle fleet. Therefore, even minor adjustments to this value result in large impacts to the energy use of the tank.

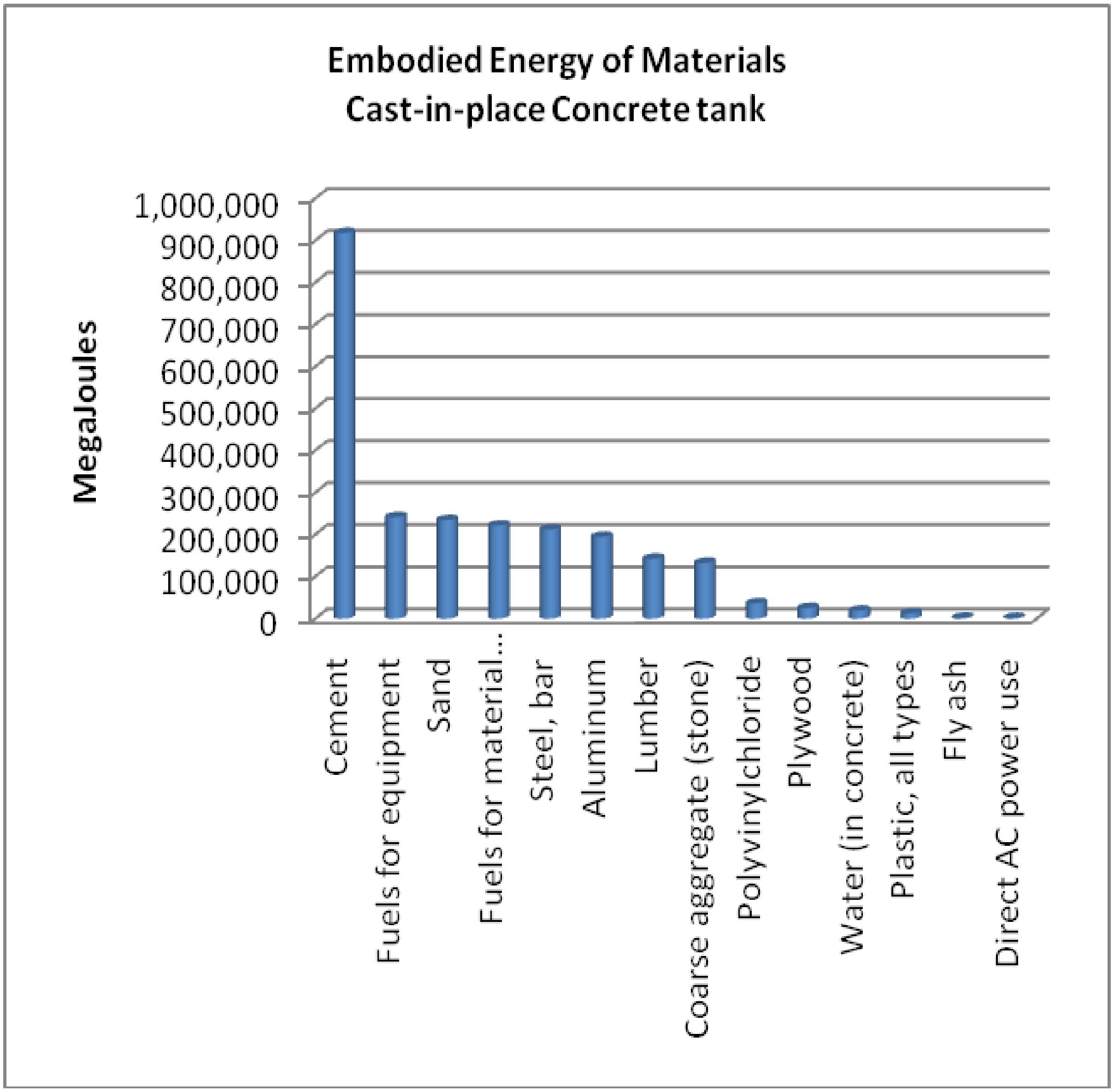

Figure 4-1. Embodied energy of materials, cast-in-place concrete tank

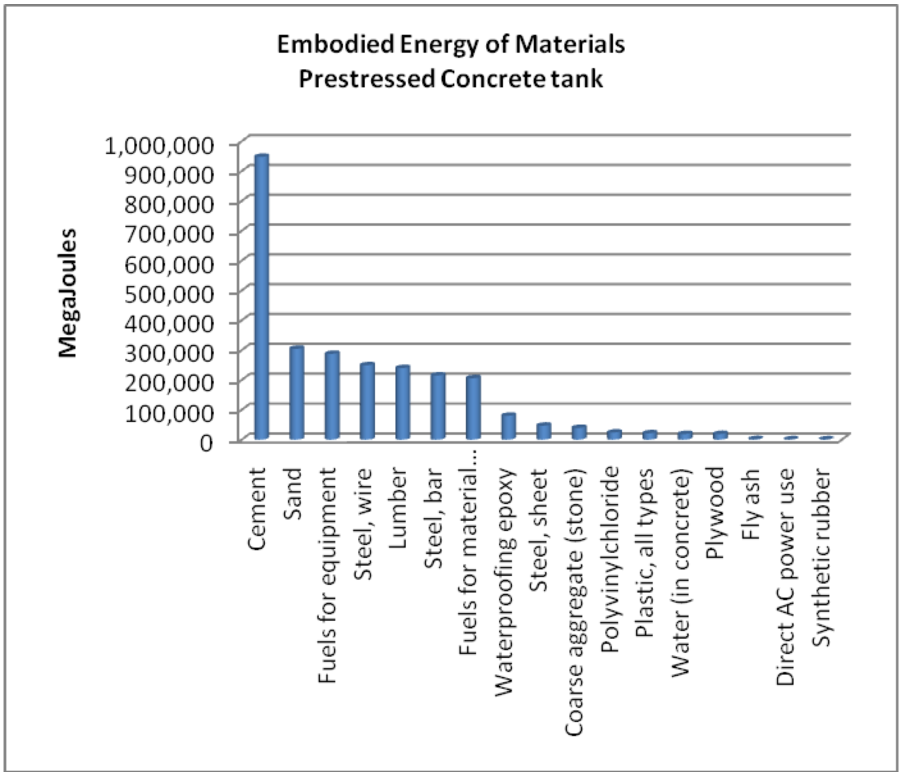

Figure 4-2. Embodied energy of materials, prestressed concrete tank

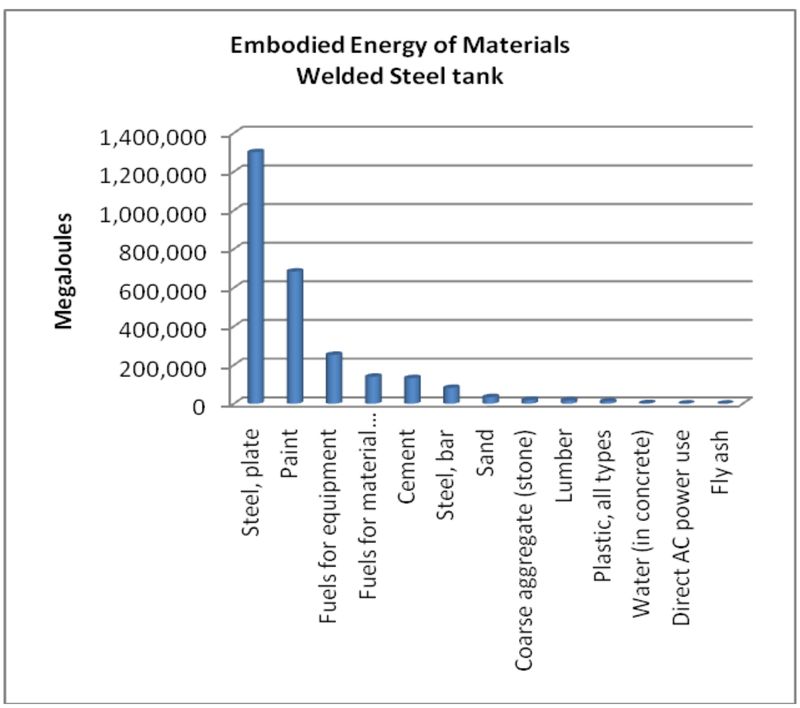

Figure 4-3. Embodied energy of materials, welded steel tank

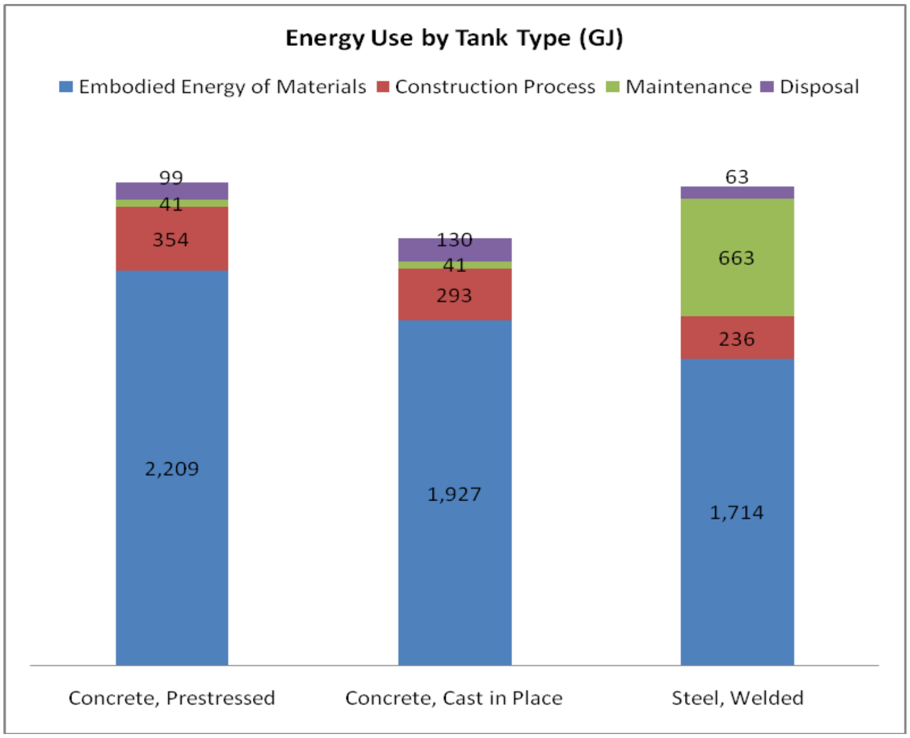

Figure 4-4. Energy use by life-cycle stage

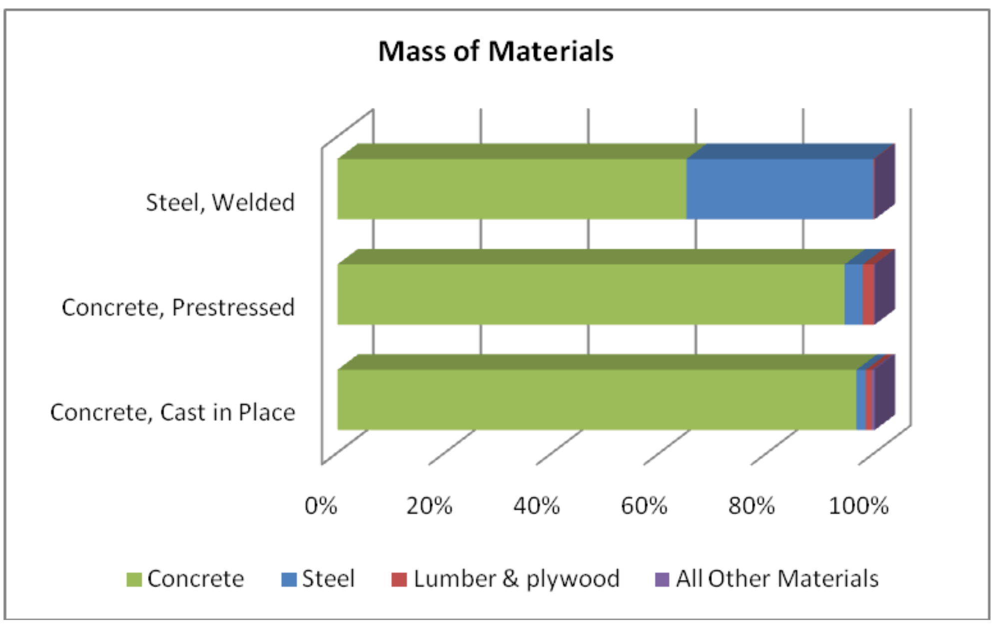

Figure 4-5 Mass of materials per tank design

Table 4-4. Comparison of energy consumption and mass

	Concrete, Cast in Place	Concrete, Prestressed	Steel, Welded
Allocation of Mass			
Concrete	97%	94%	65%
Steel	2%	3%	35%
Lumber and plywood	1%	2%	0.2%
All Other Materials	0.53%	0.11%	0.04%
Allocation of Energy Consumption			
Concrete	55%	49%	7%
Steel	9%	19%	52%
Lumber and plywood	7%	10%	0.6%
All Other Materials	10%	5%	26%
Construction Equipment and Tools	10%	11%	9%
Fuels for material transportation	9%	8%	5%

Table 4-5. Effect of transportation per mile

Transportation Category	Concrete, Cast in Place	Concrete, Prestressed	Steel, Welded
Megajoules/mile			
from shop to site (MJ/mile):	418	460	402
from concrete plant to site (MJ/mile):	1,779	1,111	256
from steel plant to site (MJ/mile):	84	63	11
from site to landfill (MJ/mile):	1,735	1,317	418
fuel efficiency (MJ/mile/gal):	27,677	25,747	17,433

CHAPTER 5
CONCLUSION AND DISCUSSION

Conclusion

This report reviewed the comparative energy use of three ground-storage water tank types over a 50-year study period, also referred to herein as their life-cycle energy use. The three tanks selected represent the majority of water-storage tanks built in the United States. The approach used by this author is to try to view the question of which tank has the lowest life-cycle energy use from the vantage point of the end-user, i.e. the plant operators and utility-maintenance organizations which commission the construction of water-tanks, trying to decide which type of water tank to spend their money on. It is understood that this is a question with a narrow focus; the actual decision of which kind of water tank works best in a given situation is complex and revolves mainly, though not exclusively, around issues of life-cycle cost to the end-user, not necessarily life-cycle energy use. However the results of this report have provided analysis of some value, it is hoped, in making that decision. The cost of energy in the United States is expected to rise in the near- to medium-term, possibly dramatically, as the US shifts from a dependence on foreign fossil fuels to more sustainable means of energy production with less carbon emissions. One possible scenario under consideration by legislators is a system of carbon caps and trading, or even a straight carbon tax, both of which would have the immediate effect of making fossil-fuel-based energy production in the United States more expensive (as is the intention). Therefore a narrow look at life-cycle energy consumption is warranted.

Discussion

Generally, all three tanks consume roughly similar quantities of energy, though the cast-in-place tank consumed the least. These results are driven almost entirely by the high proportion of embodied energy inherent in the tank design. The degree of energy consumed in the maintenance of the steel tank is also a factor, being significantly higher compared to the concrete tanks; however the energy used during initial construction is significantly less than for the concrete tanks by 33% (prestressed) and 19% (cast-in-place), respectively. If embodied energy is excluded the steel tank consumes significantly more life-cycle energy than either of the two concrete tanks.

Again these results refer only to energy use. It is entirely possible that if one considers carbon emissions in the calculation then the steel tank may ultimately be the better value in terms of any legislative action on carbon emission in the future. According to Environmental Building News, "In 2008, [Portland cement] production generated about 46 million tons (42 mmt) of CO2, compared with 0.33 million tons (0.30 mmt) for steel manufacturing…" (Ehrlich 2010, Sep). This implies the choice between concrete or steel is a complicated one. As has been pointed out by many authors, a direct ton-to-ton comparison of the impacts of either material is not appropriate, since the materials are used in different amounts in different ways on different projects. A steel column will have less mass than a concrete column of similar load-capacity, for example, and there is no easy "multiplication factor" that can be used across the board to correct for this since it depends entirely on the specific use at hand. One can, however, perform this type of calculation on narrow examples of material uses, such as in the case of ground-water storage tanks.

For this analysis a comparison was made between the prestressed concrete water tank and the welded steel tank, in order to compare the effectiveness of similar quantities of reinforced concrete to structural steel. The mass of the materials in the tank slabs, walls and dome were tabulated for each tank and a unit weight-to-unit weight comparison of steel to reinforced concrete materials was then able to be made. The results show there is a concrete-to-steel ratio of 3.49 by mass for a ground water storage tank. In other words there is a greater mass of concrete in a (prestressed) concrete tank tank than there is steel in a steel tank, in tanks of similar dimensions, by a factor of approximately three and half. This could have larger implications when calculating carbon emissions for various tank designs.

Finally, it is useful to put these energy consumption numbers into a larger context. One obvious point of comparison is these water tank numbers and a typical building. The researchers Scheuer, Keoleian and Reppe conducted a study of a new, mixed-used building at the University of Michigan in 2003 in which they determined the building's overall life-cycle energy to be 3,401 GJ/sf. That study maintained a similar system boundary as the current study. In comparison to the life-cycle energy consumption of the three water tank designs in this report, the building consumed more energy in a single square foot of space than the entirety of any of the water tank designs, by anywhere from 26-42%. The Scheur et al. study found that electricity operation accounted for 94% of total life-cycle energy, demonstrating the huge impact building operations have on the energy consumption of typical buildings. Similarly, Keolian et al. (2000) found that a standard, single family detached residential structure of 2,450 square feet consumed 16,000 GJ over a 50-year lifespan. This would be 6-7 times the value of these three tank designs. We can further make a comparison of these values to another standard fuel-consuming activity, driving. The Environmental Protection Agency (2000) estimates that an average US passenger travels approximately 12,500 miles per year and an average of 21.5 miles per gallon, consuming 581 gallons of gasoline. This would be equal to 75.5 GJ of energy. Therefore, in terms of energy consumption one of these water tanks would be equal to approximately 32-36 U.S. commuting passengers per year.

Further Research

An obvious area to expand the current study in a useful direction is to add carbon emissions and eco-toxicity values into this model and develop a full Life-Cycle Assessment tool specific to ground storage water tanks. Such a study would be able to identify broader environmental impacts associated with these three tank types, and provide a more fully-developed tool in the hands of designers attempting to choose a tank.

Another potentially productive avenue of future research is to normalize these results in terms of population served. For example, for every 1,000 people in the population how many MJ of life-cycle energy is required to provide for their water-supply needs? This type of study would have to expand substantially to include the effect of elevated and buried water tanks, tanks and equipment at waste-water treatment plants, pump-stations, and ultimately the piping in the ground which services the population. The results of such a study would provide a spectacularly useful tool for designers and policy-makers.

Finally, perhaps the most useful tool for policy-makers and designers would be to take the results of this study and develop them into dollar values. In order to do this the type of fuel for each energy use would have to be assumed and calculated. Such a study then could perhaps assume different energy cost scenarios such as (a) energy costs remain consistent through time, (b) energy costs rise by a certain percentage each year, (c) legislators pass a $30/ton carbon tax, resulting in fossil fuels becoming more expensive, (d) power plants begin to develop a greater percentage of renewable energy in their fuel mix, etc.

Ultimately it is hoped this research will provide at minimum a framework for future research regarding the energy efficiency of infrastructure designs within the context of uncertainties in the future of energy production.

LIST OF REFERENCES

American Society of Civil Engineers (1992) Design of municipal wastewater treatment plants, vol I. Brattleboro, VT: Book Press, Inc.

Best, R & De Valence, G (2002) Design and construction: Building in value. Oxford, England: Butterworth-Heinemann

Bhadauria, S & Gupta, M (2006) In-Service durability performance of water tanks. Journal of Performance of Constructed Facilities. P 136

Buchanan, H. & Honey, B (1994) Energy and carbon dioxide implications of building construction. Energy and Buildings, 20:205–217

Cole, R & Rousseau, D (1992) Environmental Auditing for Building Construction: Energy and Air Pollution Indices for Building Materials. Building and Environment, 31(1):23–30

Cole, R & Kernan, P (1996) Life-cycle energy use in office buildings. Building and Environment, 27(4):307–317

Ehrlich, B (2010, Sep) Reducing Environmental Impacts of Cement and Concrete. Environmental Building News. 19(9)

U.S. EPA (Environmental Protection Agency) (2007) Distribution system inventory, integrity and water quality. Retrieved from http://www.epa.gov/ogwdw000/disinfection/tcr/pdfs/issuepaper_tcr_ds-inventory.pdf

Facanha, C & Horvath, A (2006) Environmental Assessment of Freight Transportation in the U.S. International Journal of Life Cycle Assessment 11(4):229–239. doi:10.1065/lca2006.02.244

Flower, D & Sanjayan, J (2007) Green house gas emissions due to concrete manufacture. International Journal of Life Cycle Assessment 12(5):282–288. doi:10.1065/lca2007.05.327

Gustavsson, L & Loelsson, A (2010) Life cycle primary energy analysis of residential buildings. Energy and Buildings 42:210–220. doi:10.1016/j.enbuild.2009.08.017

Gustavsson, L, Loelsson, A & Sathre, R (2010) Life cycle primary energy use and carbon emission of an eight-storey wood-framed apartment building. Energy and Buildings 42:230–242. doi:10.1016/j.enbuild.2009.08.018

Hammond, G, & Craig, J (2008) Inventory of Carbon and Energy (ICE), Version 1.6a. University of Bath. Available from http://www.bath.ac.uk/mech-eng/sert/embodied/

Holmberg, M (2009, July) Reinforced Concrete Tank Design. Structure Magazine, 22–23

Jonsson, A, Bjorklund, T, & Tillman, A (1998) LCA of Concrete and Steel Building Frames. International Journal of Life Cycle Assessment, 3 (4), 216–224

Kibert, C (2008) Sustainable construction: Green building design and delivery. Hoboken, NJ: John Wiley & Sons

Keoleian, G, Blanchard, S, & Reppe, P (2000) Life-Cycle Energy, Costs, and Strategies for Improving a Single-Family House. Journal of Industrial Ecology, 4 (2):135–156.

Malin, N (1993, May) Embodied Energy--Just What Is It and Why Do We Care? Environmental Building News.

Monahan (2010) An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework. Energy and Buildings doi:10.1016/j.enbuild.2010.09.005 (unedited manuscript accepted for publication)

Myers, P (1997) Aboveground storage tanks. New York, NY: McGraw-Hill

O'Brian, K, Menache, J, & O'Moore, L (2009) Impact of fly ash content and fly ash transportation distance on embodied greenhouse gas emissions and water consumption in concrete. International Journal of Life Cycle Assessment, 14:621–629

Optis, M, Wild, P (2010) Inadequate documentation in published life cycle energy reports on buildings. International Journal of Life Cycle Assessment 15:644–651

Oyeshola, K, & Gheewala, S (2008). Environmental life cycle assessment of a commercial office building in Thailand. International Journal of Life Cycle Assessment 13:498–511

Pluijmert, T, Seifert, F, Schindler, A, Bathelier, X, Thomas, P, Nemuth, S… Verhulst, J (2008) Industry approach to life cycle assessment. Plastics, Rubber and Composites. 37(9/10). doi:10.1179/174328908X356563

Ramesh, T, Prakash, R, & Shukla, K (2010) Life cycle energy analysis of buildings: An overview. Energy and Buildings (42):1592–1600

Sartori, I, & Hestnes, A (2006) Energy use in the life cycle of conventional and low-energy buildings. Energy and Buildings (39):249–257

Scheuer, C, Keoleian, G, & Reppe, P (2003) Life cycle energy and environmental performance of a new university building: Modeling challenges and design implications. Energy and Buildings (35):1049–1064

Swamy, A (2007, March) Seismic Design of Ground Supported Liquid Storage Welded Steel Tanks. Structure Magazine. 22–27

TEMOR Industrial Products (2010) Product Information. Retrieved from http://www.temcor.com/docs/IndustrialProducts.pdf

Tillman, A, Svingby, M, & Lundstrom, H (1998) Life cycle assessment of municipal waste water systems. International Journal of Life Cycle Assessment 3:145-157

Venkatarama Redy, B & Jagadish, K (2003) Embodied energy of common and alternative building materials and technologies. Energy and Buildings 35:129-137

Weisenberger, G (2010, August) And the Winner is… Modern Steel Construction.

Worrell, E, Price, L, Martin, N, Hendriks, C, & Meida, L (2001) Carbon dioxide emissions from the global cement industry. Annual. Review of Energy & Environment. 26:303–29

BIOGRAPHICAL SKETCH

Gabriel Everhart was born in 1974 in Philadelphia, Pennsylvania to Derald and Christine Everhart. His mother worked for the State Department so for much of his childhood he and his family moved from assignment to assignment, mostly in sub-Saharan Africa. By the time Gabriel graduated from Brandon High School (Brandon, Florida), he had lived in 7 different countries and had attended three high schools in three different states. Always drawn to the building arts, Gabriel enrolled at the University of Florida and graduated with a Bachelors of Building Construction in 1998 while also pursuing a minor in Business Administration. After graduation, Gabriel and his soon-to-be wife Amanda continued to move around, living in Portland, Oregon; Washington, District of Columbia; The Netherlands, and Tanzania as Gabriel worked for general contractors both domestically and abroad. In 2005, Gabriel and Amanda, now with a one-year old son, moved back to Gainesville where Gabriel began working as a project manager for a prestressed concrete tank contractor and Amanda pursued a Masters Degree in Nursing. During this time, two more children were born, both girls. In 2008, Gabriel returned to the University of Florida part-time to pursue his Masters Degree in Building Construction while continuing to work full time and raise three small children.