December 5, 2008
CEE 226: Life Cycle Analysis
Final Term Project

LCA Comparison of Two Aquarium Tank Systems: Fiber-Reinforced Plastic and Concrete

Evrydiki Fekka, Forest Flager, Nick Frieden, Tom Mercer, Sarah Russell-Smith

Abstract

This paper presents the results of a Life Cycle Assessment (LCA) of two competing aquarium tank systems considered for purchase by the Monterey Bay Aquarium Research Institute (MBARI) in Monterey, California. The two options were a primarily fiber-reinforced plastics (FRP) design created by Kreysler & Associates and a steel-reinforced concrete design engineered and estimated by Rutherford & Chekene. The aquarium chose the FRP option, but after a discussion about the tank's environmental qualities, it was decided that Kreysler & Associates would also pursue an LCA to gather more information about whether in fact the FRP tank was a more environmentally sustainable choice. The purpose of this LCA is to answer that question.

The functional unit in this process-based LCA is the provision of tank "holding" services for 20 years. Both tanks are assumed by Monterey Bay Aquarium Research Institute to have the same expected durability, damage risk, as well as maintenance and cleaning schedule. This is a comparative LCA, processes and phases that were the same between the systems were not included in the LCA process and results, but none of these were significant drivers of any metric. Therefore this analysis represents realistic absolute value outputs, as well. The system boundaries for the LCA include everything from raw material production to end-of-life disposal, but do not include adjacent systems, such as pumping of water into and out of the tank or gelcoat applications.

The life cycle impact assessment revealed that the FRP tank performed well against the concrete tank in terms of life cycle greenhouse gas emissions, solid waste, energy resources, and acidification—our higher order impact categories. Much of the impact of both systems lies in the raw material production stage, particularly focused around the bonding material in each of the tanks. In the case of the concrete tank, the main driver for both solid waste and greenhouse gas emissions was the cement that held the tank together. Similarly, in the case of the FRP tank, production of the resin was the biggest driver of energy requirements. There is some uncertainty around the polyester resin type used in the FRP and the impact that would have on the life cycle energy resources for the system, so we ran a different scenario with epoxy resin that establishes an upper bound and sensitivity of the impacts to the resin choice.

In every major category, the FRP tank is a more sustainable solution, and we recommend further development and deployment of this aquarium tank design. It is also worth noting here that in this situation, the Monterey Bay Aquarium's environmental and financial interests are well aligned, since the life cycle costs for the FRP tank were $300,000 lower as well.

Introduction

This paper presents the results of a process-based life cycle assessment (LCA) conducted to compare the impacts of two marine aquarium tank designs considered by the Monterey Bay Aquarium Research Institute (MBARI). The two tank constructions considered were a primarily fiber-reinforced plastics (FRP) design created by Kreysler & Associates and a steel-reinforced concrete design engineered and estimated by Rutherford & Chekene. The aquarium chose the FRP option, but as a condition of the contract, they asked that Kreysler & Associates pursue an LCA to gather more information about whether in fact the FRP tank was a more environmentally sustainable choice. The following analysis is designed to answer that specific question, and in the process, understand the underlying drivers of comparative environmental impact, cost, and performance in these two built systems that could be generalized and applied to other systems.

The paper will progress from a brief summary of the two tank systems, to a rundown of the LCA methods and data used here, to an inventory and impact assessment results, which are presented phase-by-phase to highlight differences between the FRP and concrete. The paper will close with aggregate results and assessment, along with recommendations for possible improvement of the FRP process.

FRP and Concrete Tank Processes

Before digging into the details of the LCA, it is worthwhile to run through the processes and process flow diagrams for both the FRP tank and the steel-reinforced concrete tank to understand the basics before diving into further analysis.

The steel-reinforced concrete is the typical construction process for a structure of this sort. The builder would truck in the rebar, concrete, and wooden formwork from offsite, and then set the formwork and rebar in place with a forklift. The concrete would be applied as shotcrete with a pump, and then the tank would dry. A catwalk would then be added, although it would serve no structural purpose. Wooden formwork would be returned to the contractor and reused. The tank would then be in use for its 20-year life. At end of life, this model assumes that 100% of the steel would be salvaged—although presumably it would be hard to separate from the concrete—and the steel would go to the landfill. For the full process flow diagram, see Exhibit 1. A diagram of the SRC tank can be seen in Exhibit 2.

The FRP tank's construction process is a bit unusual for a structure of this sort. It all begins with low-energy glass fiber from Owens Corning and a polyester resin from Ashland Chemical. These two materials are combined and set through a wet hand layup process. The glass fiber is laid out on top of a waxed steel mold, and then the resin is applied with a roller. The panels are then cured at room temperature for 4-5 hours to achieve 95% cross-linking. The mold side of the FRP is then sandblasted to achieve a proper surface profile, and steel ribs are attached with an adhesive. The panels are trucked to the site in three separate loads, and once there, a forklift is used to put them in place. The panels are bolted together, and FRP strips are applied to cover the seams between panels. The two catwalks are then attached to the top of the tank. These catwalks actually provide structural support to the top of the tank to hold them in tension and keep the panels from bending outward.[1] This system also has an anticipated life of 20 years. At end of life the panels are unbolted from their steel supports, and both the steel ribs and supports are salvaged. The rest of the tank is FRP, which is disposed of at the landfill. For a full process flow diagram, see Exhibit 3, and for a diagram of the FRP tank, see Exhibit 4.

LCA Methods, Boundaries, Impact Categories, and Data

As mentioned above, the LCA of the two tank systems is a process-based analysis that we modeled in the SimaPro software suite. The functional unit is 20 years of holding seawater and marine life, although, in this case, it is effectively the same as a functional unit of one tank, because each system is projected by MBARI to last a full 20 years.

The boundaries of the systems are drawn such that everything from material production to end-of-life is considered. Adjacent processes or materials are considered to be outside the system boundaries. For example, the energy to pump water in and out of the tank and the gelcoats applied to both tanks, are considered to be outside the system boundaries. Moreover, because this is a

---

[1] Kreysler, W., 2008.

comparative LCA, the system boundaries exclude any phase where there is not a significant discrepancy between systems. A good example of this is the use phase; the information provided by MBARI suggests that each tank has an annual cleaning, and in both cases, the gelcoat may be damaged by fish collisions with the tank walls and require a reapplication at some point. However, there is no significant difference in the way the two systems are maintained, so the entire use phase is disregarded for the purposes of this LCA.

The following chart shows the emissions and impacts that this LCA focuses on most closely:

Emissions	***Impact Categories***
• Carbon Dioxide • Carbon Monoxide • NOx • SOx • Particulate Matter • Volatile Organic Compounds (VOCs) • Solid Waste • Process- and Material-specific waste issues	• Total Energy Resources • Greenhouse Gas Emissions • Ozone Depletion • Acidification • Eutrofication • Heavy Metals • Carcinogens • Summer Smog Formation • Winter Smog Formation • Solid Waste

In the impact assessment that follows, analysis will focus particularly on total energy resources, greenhouse gas emissions, solid waste, and acidification.

Although this LCA relies heavily on the Eco-Indicator 99 database in SimaPro, there were a few other data sources that provided assistance and clarification for specific portions of the LCA, including the following:

- Eco-Indicator 99 Database (SimaPro software) was the default database
- Owens Corning Advantex Glass Fiber: information on emissions reductions and higher performance[2]
- Cost and fabrication data from Kreysler & Associates and MBARI
- Confidential polyester resin data from Ashland Chemical

Life Cycle Cost Analysis

Before doing an environmental impact assessment for the two systems, it is useful to set up a life cycle cost analysis to understand the economic factors at play. Luckily, a cost estimate was available for the concrete tank, and the quote for the FRP tank was obviously available as well. The upfront cost, therefore, was just a matter of pulling quotes rather than more arduous bottom-up costing.

Purchase price is not the only life cycle cost, however. There is an end-of-life cost of disposing of the tank in 20 years, which consists of transportation to the municipal waste facility and the tipping fees required to dispose of waste there. The tipping fees for the Monterey Regional Waste Management District are $45 per ton.[3] To account for the cost of transportation to the municipal waste facility, I simply assumed that it would be approximately the same as the tipping fee and doubled that charge to take it into account. The use phase maintenance of the tank could be another potential source of cost, but since it is outside the boundaries of this LCA, it is not considered in the life cycle cost analysis either.

---

[2] JEC Composites Web Site, 2008.

[3] Monterey Regional Waste Management District, 2008.

To figure out the total life cycle cost, it is necessary to set up a discounted cash flow model and bring the end-of-life costs back to present value. To do so, this LCA used a discount rate of 3%; the rate is so low, because of the high probability that tipping fees and waste disposal will get more expensive going forward. The following is the breakdown of cost by phase:

	FRP Tank	**Concrete Tank**
Agency Costs	$1,501,935	$1,836,763
Use Phase Costs	$ -	$ -
End of Life Costs	$4,161	$15,537
Total LCC	**$1,506,096**	**$1,852,300**

The purchase price of the tank represents the vast majority of the life cycle costs of these tanks, but more importantly, the FRP tank outperforms the concrete tank on cost both at purchase and again at end of life. Without a more detailed bid, it is hard to know why the sticker price for the tank is lower, but at end of life, the main driver of cost is tonnage, and the FRP is much lighter than its counterpart.

Impact Assessment Results by Phase

As mentioned above, the impact assessment comparison and analysis are broken out by phase below in order to make sure contrasts in process and materials are given sufficient attention. Key assumptions are stated up front, followed by results and key drivers for those results.

Material Production Phase - Assumptions

For the FRP in the material production phase, the only raw materials used are polyester resin, glass fiber, steel (for ribbing), and concrete (for the platform beneath the tank). These material inputs have to be scaled to take into account a 2% waste factor for the resin and a 5% waste factor for glass fiber. In terms of processes, the material production phase also includes the hand layup, as well as the sandblasting. To model the sandblasting, we include outputs for a 50 horsepower engine for three hours, as well as 150 pounds of 30 mesh kiln dried silica blasting grit, which would be recycled once per hour.

This is also the phase that accounts for the embodied and process energy required to produce the resin, which turns out to be an issue in this particular case. Because resin makes up fully 58% of the FRP and some manufacturing processes to generate resin are extremely energy intensive, it is important to have the resin data be as accurate as possible. As mentioned in the LCA data sources section, Ashland provided the recipe for the specific resin that was used for this FRP tank, but it would have been very arduous (and beyond the scope of this LCA) to proceed from that recipe to life cycle inventory data. Thus, it was necessary to find the most comparable resin in the SimaPro database and use that. Unfortunately, the polyester resins available in the database ranged in inventory data by a factor of five or more. Upon further research, it was found that energy requirements for the production of polyester resin ranged from a 1% to 20% of energy requirements for the production of expoxy resin.[4] In the absence of better information, we decided to take a different approach, which was to model a lower-energy polyester resin, but to also substitute an epoxy resin and see how that might change the results. Fortunately, the concrete tank

---

[4] Li, W. and L.J. Lee, 2000.

is significantly simpler to model in the material production phase. There are only three material inputs—concrete, steel, and timber-and-plywood formwork—and no related processes.

Material Production Phase - Results

See Exhibit 5 for charts showing the percentage of impact for each component of each system, as well as Exhibit 6 for a spider chart comparing the impacts between the systems in every impact category. Unequivocally this data shows that the FRP tank has a lower environmental footprint in the material production phase than the reinforced concrete tank.

In the case of the concrete tank, the clear driver for most environmental impacts is the level of steel reinforcement in the reinforced concrete. In this case, the steel is making up only 4% of the total tank by weight, but its impacts in the raw materials phase are much larger than that. The formwork also has an outsized contribution relative to its weight, especially in the categories of solid waste and summer smog.

The FRP impact assessment is particularly interesting, because even though the tank is designed out of FRP, the concrete foundation for the tank outweighs the tank itself by a factor of eight. Therefore, the impacts associated with steel and concrete in this tank system are still formidable. Also note that sandblasting has a negligible effect on most impact categories. Another interesting note to consider is displayed in Exhibit 7, which shows the impacts for a system in which epoxy is the resin instead of polyester resin, as well as another spider diagram normalizing and comparing the concrete materials phase to the FRP/Epoxy materials phase. Clearly, epoxy is much more energy intensive and polluting per unit of weight than polyester, but even an FRP system with 58% epoxy would be better in the material production phase than a reinforced concrete tank.

Transportation and Construction Phase - Assumptions

In this phase, the FRP panels travel on three trucks from Kreysler & Associates' location in American Canyon near Napa, CA to Monterey, CA and we assumed that the concrete and steel travel by truck to Monterey from halfway to the nearest large industrial center, Hayward, CA. The only other process subsumed in this phase is the operation of the forklift—we modeled forklift operation as a 50 horsepower generator operating for 16 hours.

The concrete tank has similar processes in this phase. The concrete and steel, as mentioned above, are assumed to come halfway between Monterey and Hayward, and the formwork travels from the nearest lumber yard, which is 20 miles away. In terms of other processes, another forklift is needed here to place the rebar and the formwork, so the same horsepower assumptions hold here. Additionally, a concrete pump is needed to spread the concrete, which is another 33 horsepower generator operating for six hours.

Transportation and Construction Phase - Results

See Exhibit 8 for charts showing the percentage of impact for each subprocess in this phase, as well as Exhibit 9 for a spider chart comparing the impacts between the systems in every impact category.

The results of this particular phase are fairly straightforward in that the reinforced concrete tank has nearly 80% more material by weight being shipped to the site for construction, driving the transportation impacts above FRP. Even though the FRP is traveling a greater distance from Napa, CA that is not enough to offset the sheer mass being shipped for the reinforced concrete tank.

On the construction side, the forklift hours and impacts are the same for both systems, and the concrete pump used to apply the concrete has a relatively small role to play in all impact categories compared to the impacts of trucking everything to the aquarium site.

End-of-Life Phase - Assumptions

Because the municipal dump and scrap metal yard are co-located on Monterey Peninsula, all concrete, steel, and FRP goes to the same place, about 12 miles away from the aquarium site. For FRP, it follows that all material goes to the dump, and while 100% of the steel ribs are recycled, everything else is landfilled. For the concrete tank, the steel and concrete also go to the municipal waste site with the steel being 100% recycled. Presumably, the steel would be extracted from the shotcrete and there would be no losses. The formwork is handled differently, because we assumed that it is possible to get four uses out of it. Therefore, in the accounting, 25% goes to the landfill, and the other 75% is transported approximately 26 miles back to the contractor's storage yard.

End-of-Life Phase – Results

The gross impacts from the end of life phase incorporate two separate elements: the impacts associated with transporting the waste to the landfill, and impacts associated with the decomposition of waste in the landfill. And there's another twist regarding end of life inventories and impacts. SimaPro automatically subtracts the embodied inventories and impacts of all the materials that are recycled, therefore netting out the impacts of the landfilled materials.

In order to get a good sense of the relative end-of life impacts, we chose to look at the impacts in two ways. First, we extracted the data from SimaPro to compare the impacts for the landfilled concrete, FRP, and formwork less the impacts of the recycled steel and formwork. That data is presented in Exhibit 10. This graph gives a relative sense of the net end-of-life impacts including recycling. The FRP tank appears to outperform the concrete tank here, but because the net effects of the steel weigh more greatly as a proportion of the FRP system, which is much less massive, these results are distorted.

Another presumably more accurate way of looking at the end-of-life impacts of the two systems is to ignore the net negative recycling impacts and just look only at the positive landfill impacts on a relative scale. This data is presented in Exhibit 11. This chart presents a more realistic and even account of the end-of-life phases for the concrete and FRP tanks. The total energy resources required for the end of life stage is much higher for concrete tank, which makes sense, because more energy is expended hauling the heavier materials to the landfill. On the other hand, the greenhouse gas emissions for the FRP tank are much higher, which is harder to explain. We presumed that the model might account for the future breakdown of the resin into greenhouse gas byproducts, or there might be some other unexplained process working in SimaPro.

Note that for the total impact assessment where the individual phase impacts are rolled up, the positive end-of-life impacts for landfill *are* included, but the net negative impacts that SimaPro creates for recycled material *are not.* We made this judgment, because we felt it was not accurate for the producer to be able to net out the impacts of a material just because it entered a recycling stream.

Total Impact Assessment

Stepping back and looking at the whole system at once, it is clear that the FRP tank is a clear winner and has significantly lower environmental impacts in every category. Below is a chart that summarizes the absolute advantage that the FRP has in every category along with the notable percentage greater impact the concrete has than the FRP.

Impact category	Concrete	FRP	Difference	% Difference
Acidification (kg SO2)	271.5325	118.2368	153.295761	130%
Carcinogens (kg B(a)P)	0.008818	0.005539	0.00327931	59%
Energy resources (MJ LHV)	560,042.3	278,286.3	281755.998	101%
Eutrophication (kg PO4)	28.02	11.75	16.26	138%
Greenhouse (kg CO2)	36,497.22	16,552.51	19,944.70	120%
Heavy metals (kg Pb)	0.30	0.19	0.11	58%
Ozone layer (kg CFC11)	0.0009	0.000647	0.0002	38%
Pesticides kg act.sub)	0	0	0	NA
Solid waste (kg)	283,064	77,187.87	205,876.13	367%
Summer smog (kg C2H4)	18.61	7.34	11.25	153%
Winter smog (kg SPM)	3,366.19	841.76	2524.44	300%

To put these numbers all in perspective, the benefit in Greenhouse Gas Emissions is like not driving 52,486 miles in a standard automobile.[5] The benefit in acidification is like not burning 11.3 metric tones of unscrubbed U.S. (average) coal.[6] The life-cycle energy saved by the FRP tank over the concrete tank would be enough to power 12 average PG&E residential customers for a year.[7] For a closer look at how the two systems stack up against one another and individually, see Exhibits 12 and 13.

We know, however, from the data gathered that if the FRP incorporated epoxy resin instead of polyester resin in the same ratio, the life-cycle energy resources would switch and all of a sudden, the concrete tank would be more energy efficient by a factor of three.

Given our fairly high confidence, though, that the specific Ashland polyester resin used by Kreysler & Associates is closer to the polyester resin that we modeled rather than the higher-energy epoxy, we feel comfortable giving a full endorsement to the FRP tank system from an environmental impact standpoint.

Recommendations

The final section of this life cycle assessment will address ways that the FRP tank system could be improved from a life-cycle perspective, such that it could be even more resource efficient and superior to its reinforced concrete counterpart.

The first suggestion to improve the FRP system would be to replace the sandblasting of the FRP with a surface profiling roll system to achieve the same anchor profile for gelcoat without all the mess. Although sandblasting did not pop to the top of our list as one of the biggest impact-causing activities during the tank construction, it does seem like one of the least necessary components of the whole process. Not only is energy expended by the blaster, but the blast grit is just extra waste that must be disposed of. Furthermore, Bill Kreysler himself suggested that the area in his shop set aside for blasting was quite large and therefore space-inefficient. The surface profile paper system would work by rolling out a large sheet of profile paper on the FRP during layup while it is still tacky. The paper would lend its profile to the surface and peel off easily when the FRP is hard.

---

[5] Data Source is GREET 2, Version 2.7a software.

[6] Franklin Associates, 2000.

[7] Pacific Gas and Electric Company Carbon Footprint Calculator, 2008.

Another suggestion for further improvement of the FRP process would be to do vacuum layup, such that the emissions produced during the layup process could be captured and not released into the atmosphere as they are now.

Finally, a longer term suggestion for improvement of the FRP process is to find a cost-effective way of recycling the FRP at the end of life, rather than landfilling it. One of the reasons that the steel in the two tanks doesn't have a greater life cycle environmental impact on the two systems as a whole is because the steel is recycled. Obviously, there are major problems with recycling a composite material, because it is quite difficult to separate out the two components into different waste streams to be reused. If a technology was developed to make this separation process more effective or high-value use was found for scrap FRP, the impact on both this FRP tank system, but also many other applications of FRP would be improved greatly from a life-cycle environmental impact perspective.

Initial research into FRP recycling indicates that the process can be rather difficult. Japanese FRP manufacturers and end users recycle the material by incinerating it to extract some of the production energy as heat to produce electrical power. The possibly hazardous ash byproducts and dubious energy extraction efficiency make this option attractive in the US only if tipping fees rise substantially. Only one US vendor sells FRP recycling equipment believed to be commercially viable. Their method and viability was cited in a paper on FRP recycling published by the Minnesota Technical Assistance Program and is available online.[8] Their initial review of the technology and vendor was tentative, but promising. They offer a full line of commercial FRP recycling equipment and a consulting department to design custom solutions for their clients. This option should definitely be explored to determine its compatibility with Kreysler's FRP production process.

---

[8] Bartholomew, K., 2004.

Bibliography

Bartholomew, K. Fiberglass Reinforced Plastics Recycling. Minnesota Technical Assistance Program (2004).

Data Source is GREET 2, Version 2.7a software. UChicago Argonne, LLC.

Franklin Associates. Energy Requirements and Environmental Emissions for Fuel Consumption. Prepared for Greg Keoleian. December 2000

Goto, M., , M. Sasaki, and T. Hirose. Reactions of polymers in supercritical fluids for chemical recycling of waste plastics, *Journal of Material Science*. **71**, 1509-1515 (2006).

Kreysler, W. Telephone interview with Forest Flager. October 28, 2008.

Li, W. and L.J. Lee, Low temperature cure of unsaturated polyester resins with thermoplastic additives: I. Dilatometry and morphology study, *Polymer*. **41**, 685-696 (2000).

Monterey Regional Waste Management District. "Current Disposal Fees Effective February 1, 2008." Retrieved December 4, 2008.
http://www.mrwmd.org/pdf/2008_Disposal_Fee_Brochure.pdf.

Pacific Gas and Electric Company Carbon Footprint Calculator. Retrieved December 4, 2008.
http://www.pge.com/includes/docs/pdfs/about/environment/calculator/assumptions.pdf.

Exhibit 1: Reinforced Concrete Process Flow Diagram

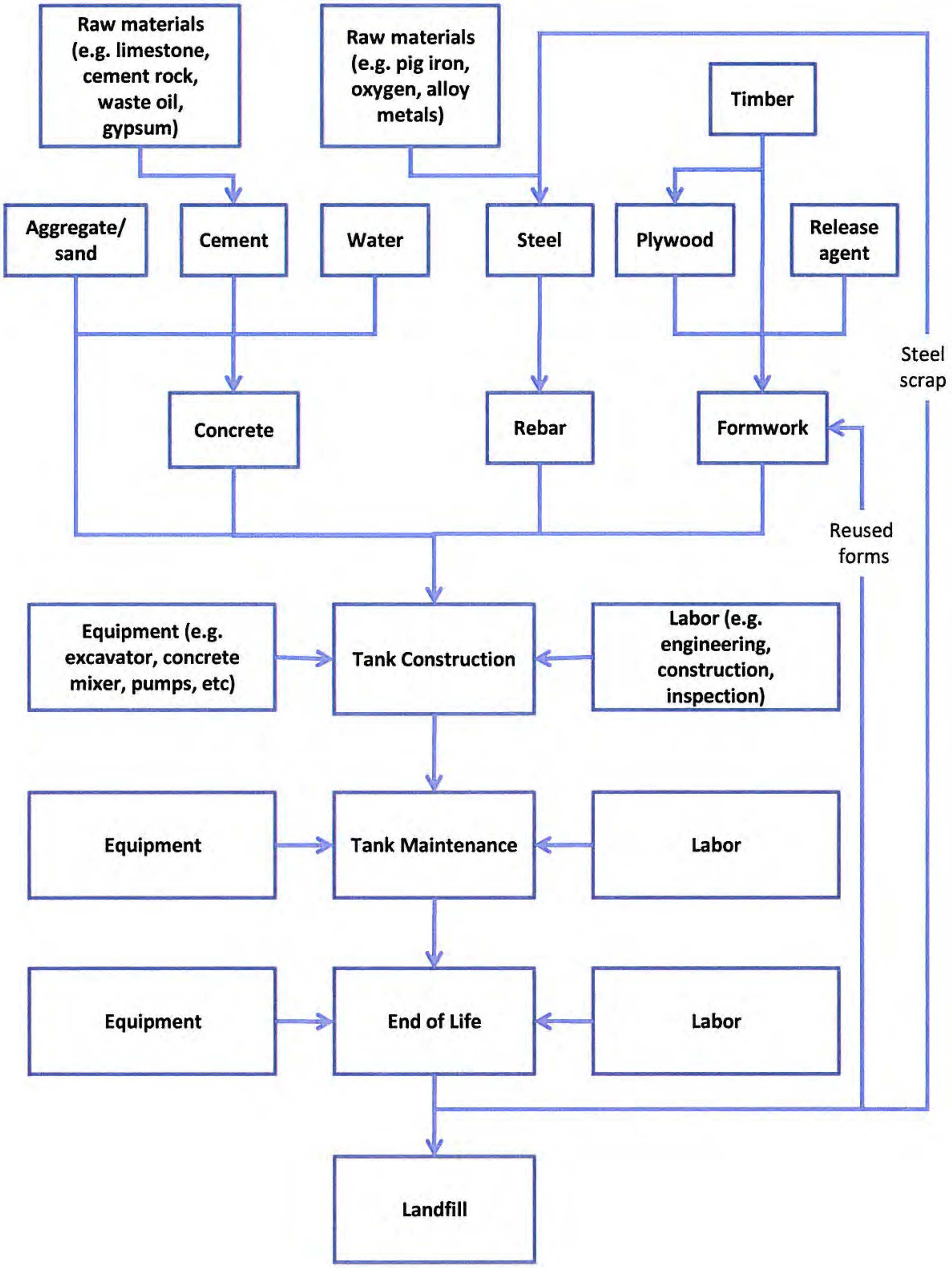


Exhibit 2: Reinforced Concrete Model

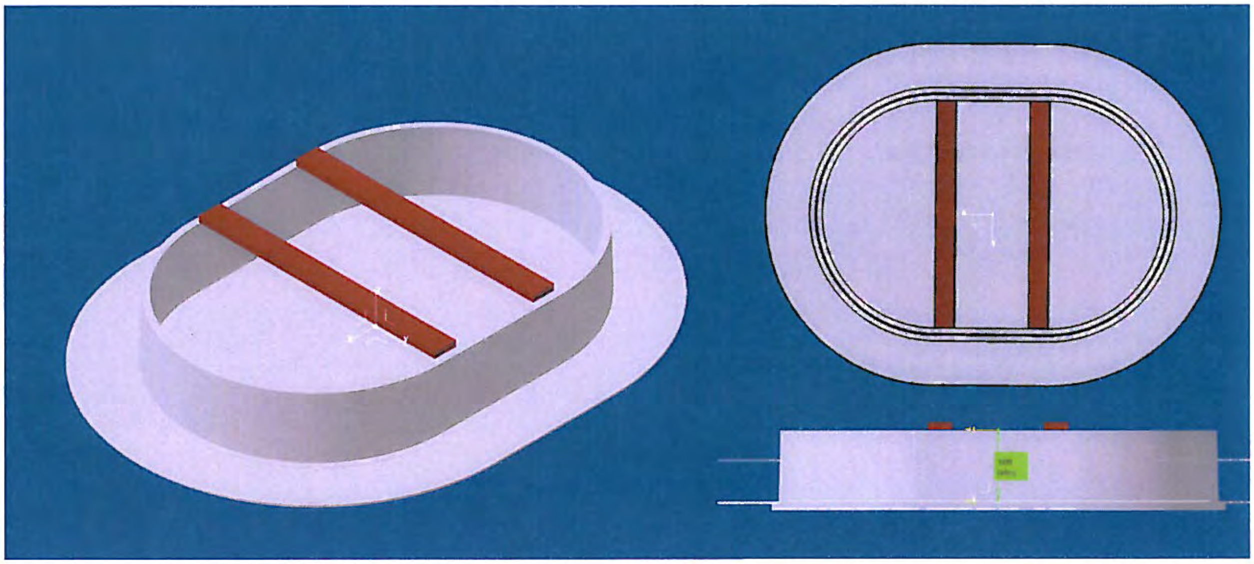


Exhibit 3: FRP Process Flow Diagram

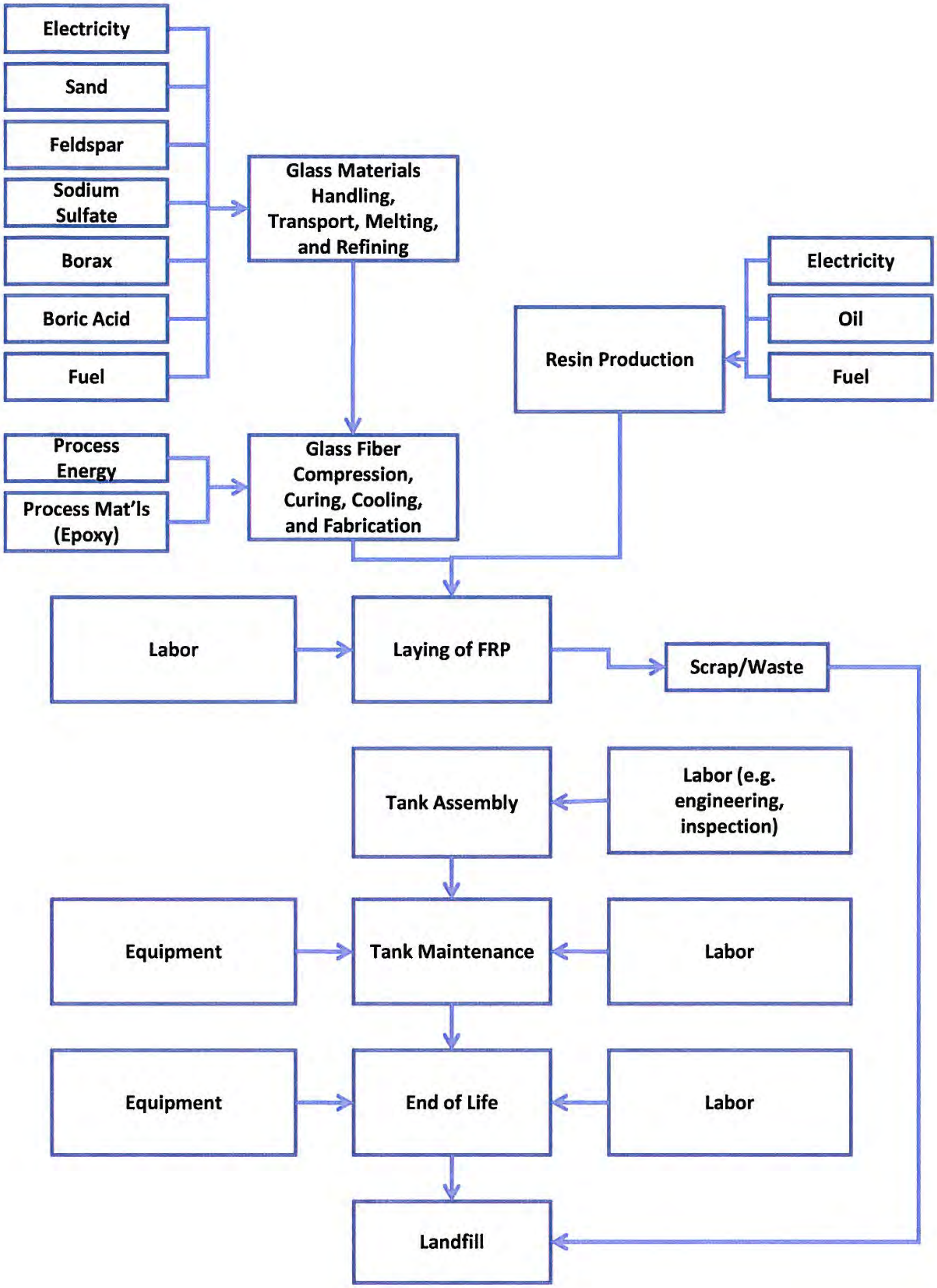


Exhibit 4: FRP Tank Model

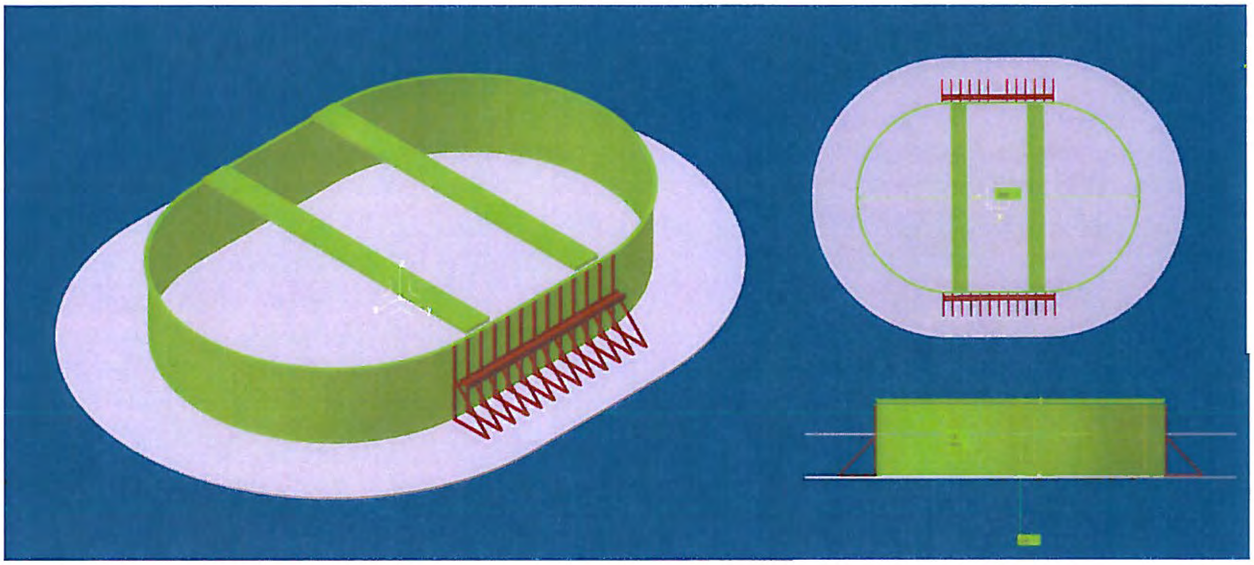
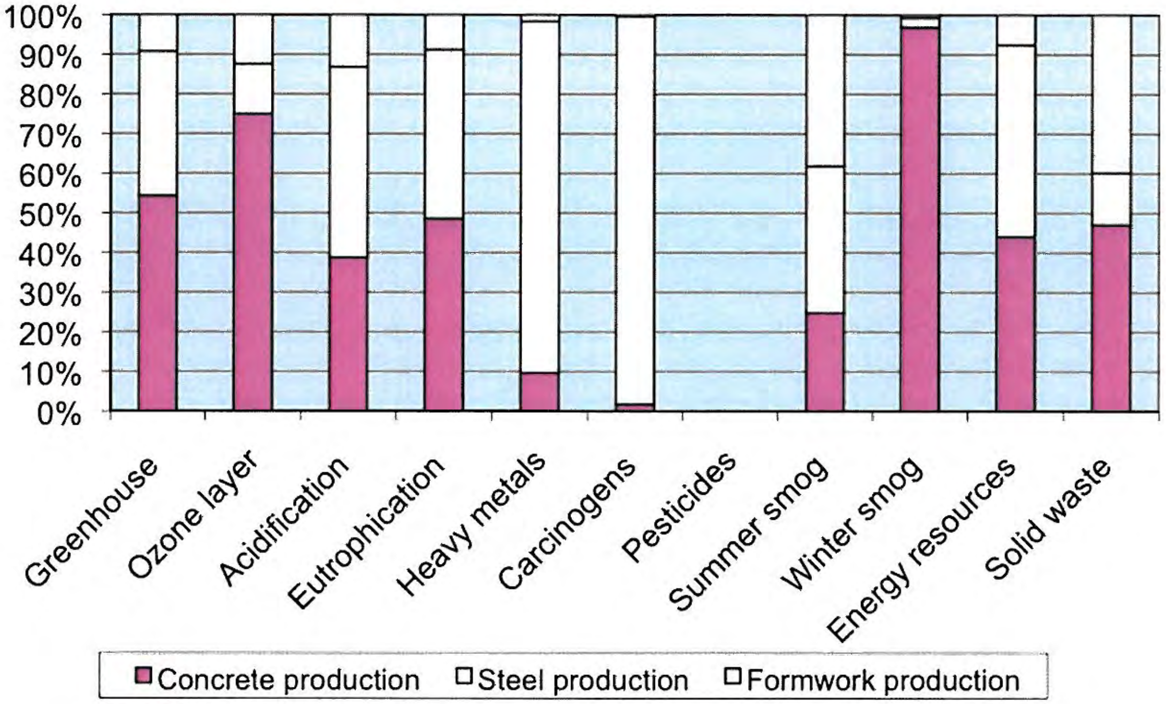


Exhibit 5: Material Production

Concrete Tank



FRP Tank

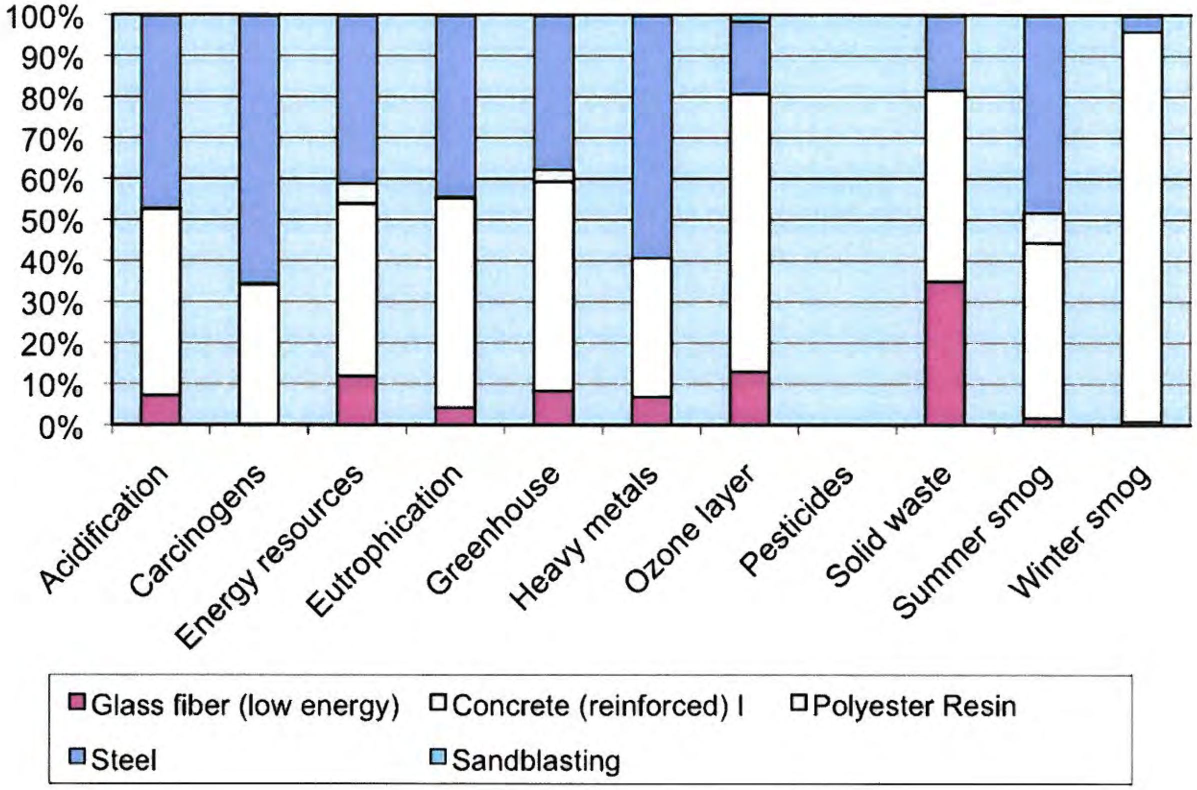


Exhibit 6: Material Production Comparison

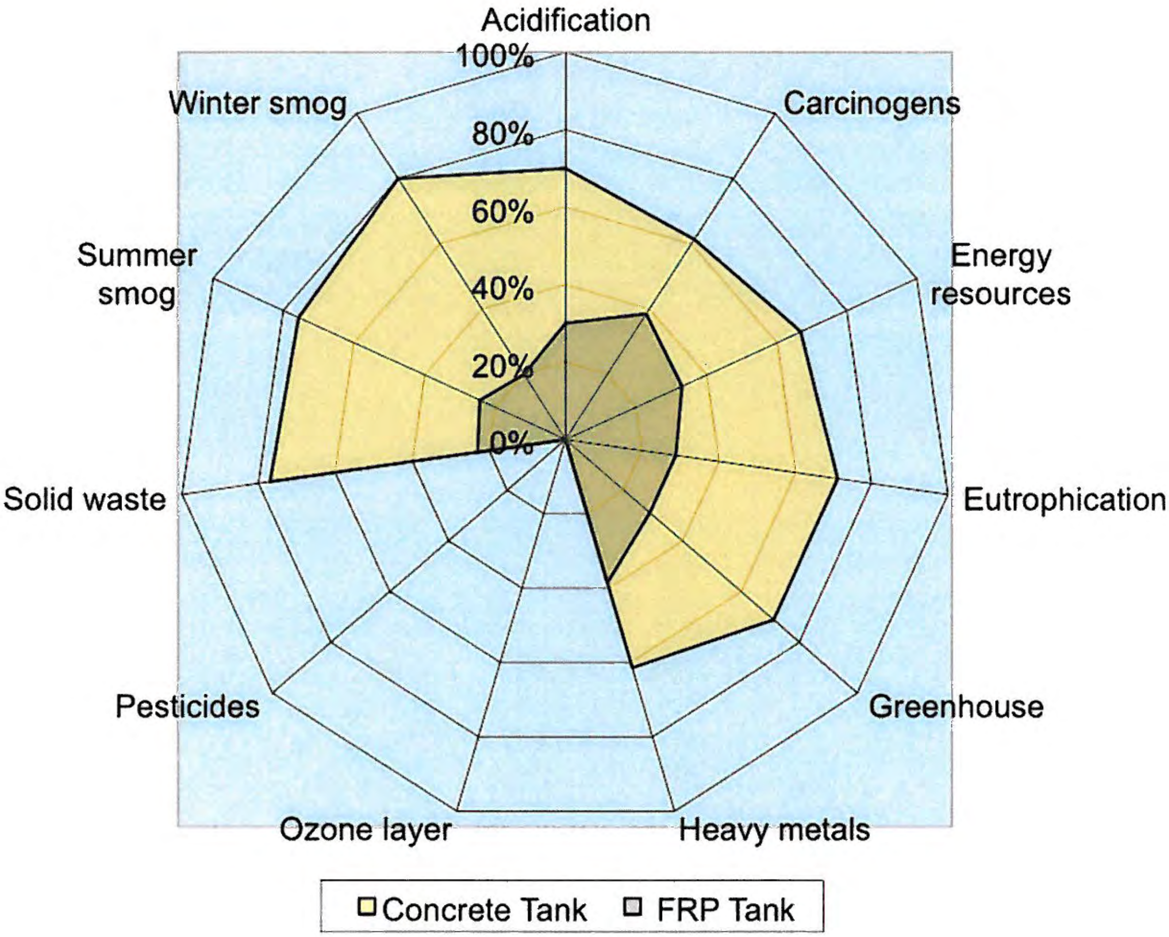


Exhibit 7: Material Production (Comparison w/ Epoxy)

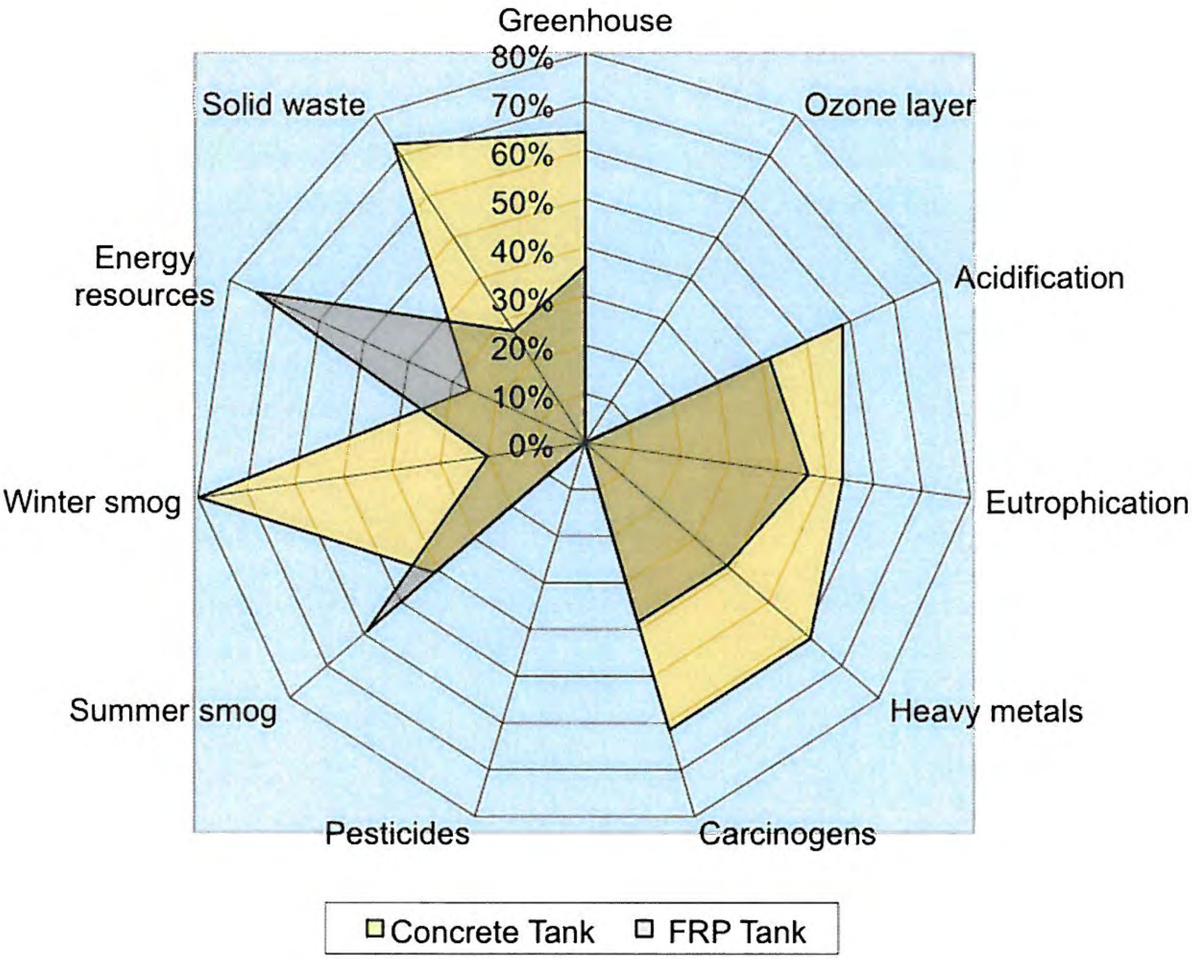
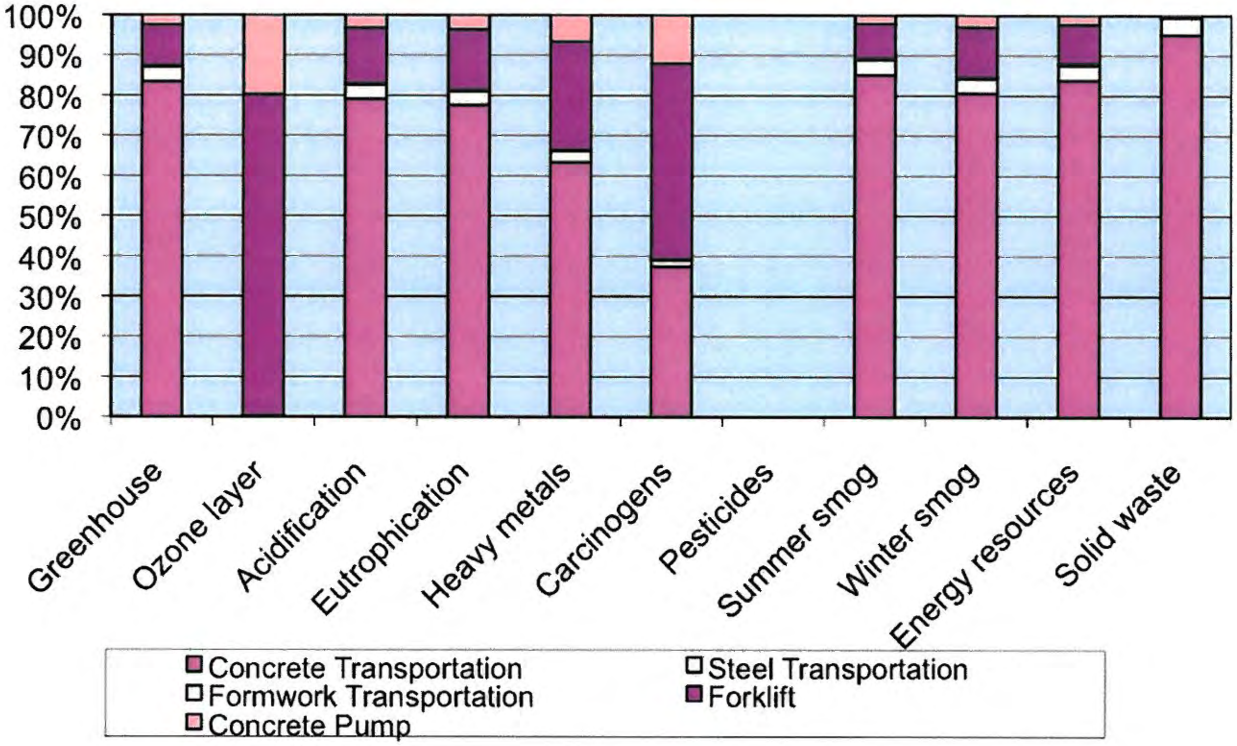


Exhibit 8: Construction/Transportation

Concrete Tank



FRP Tank

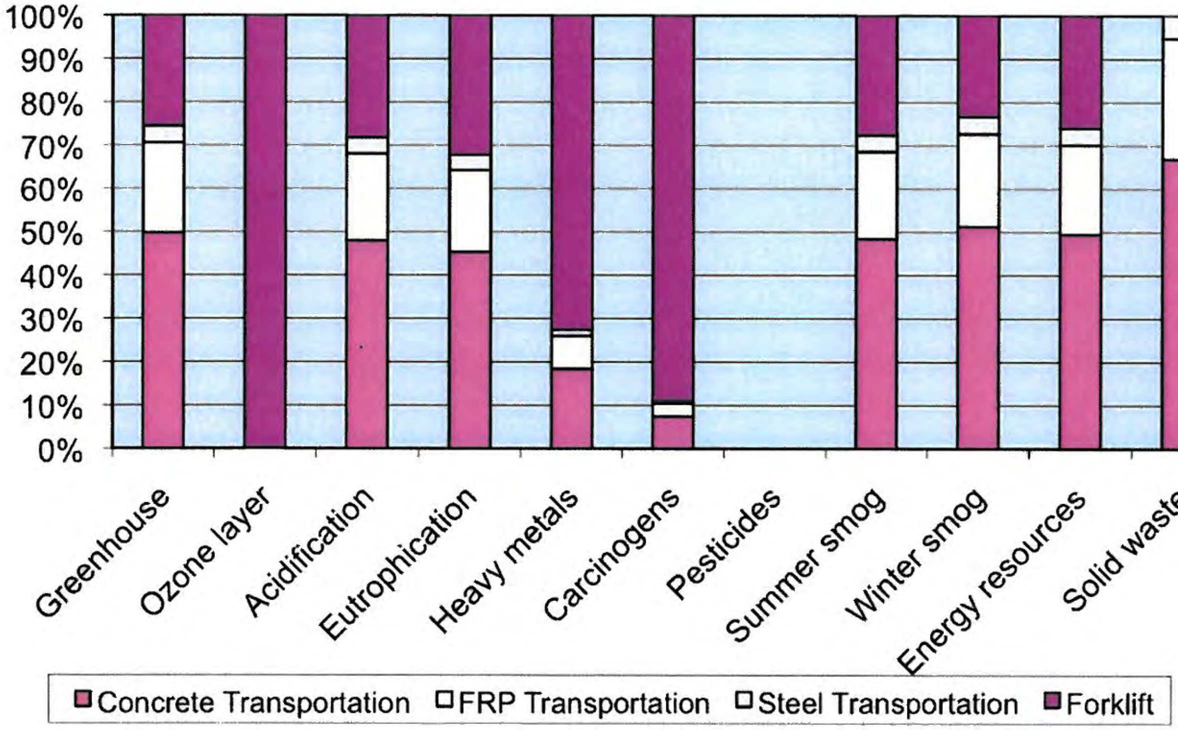


Exhibit 9: Construction/Transportation Comparision

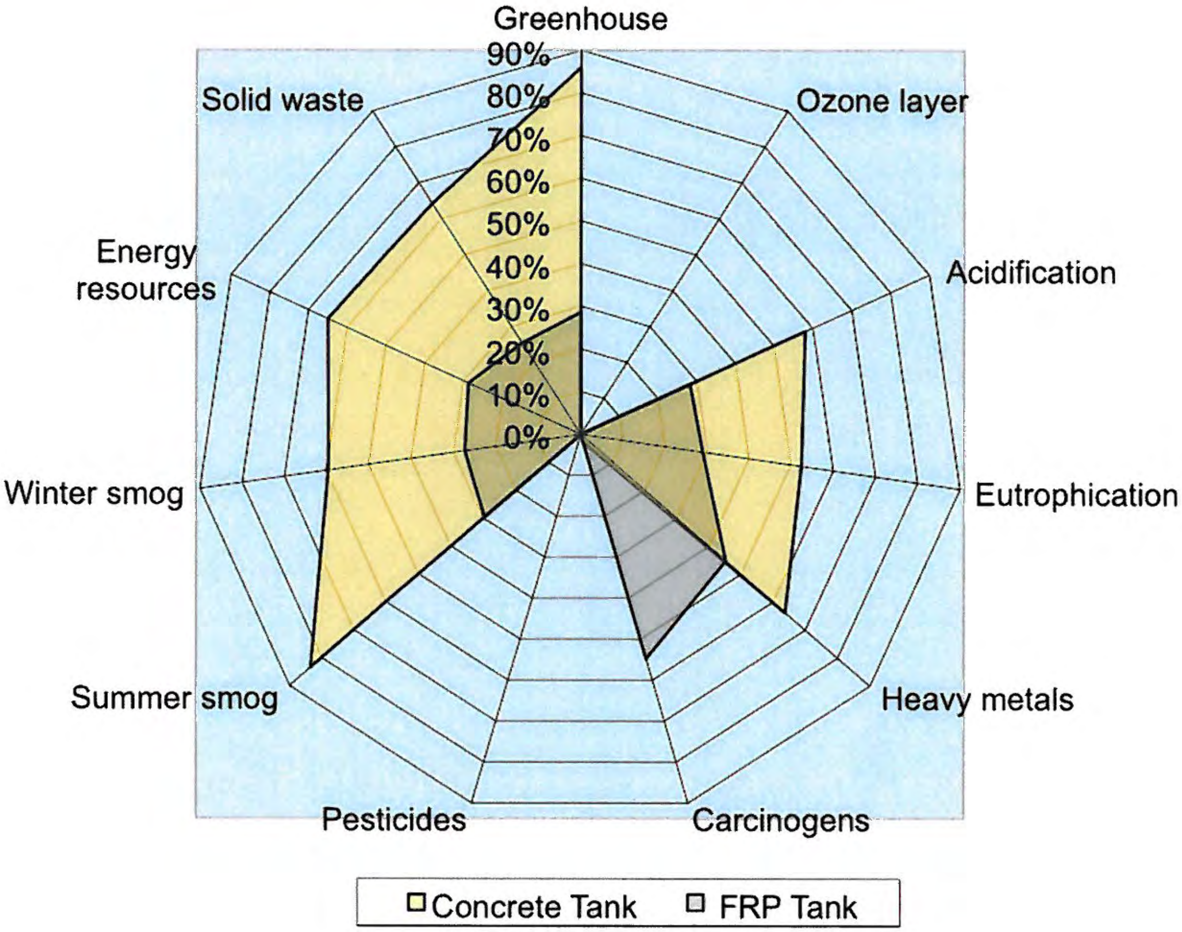
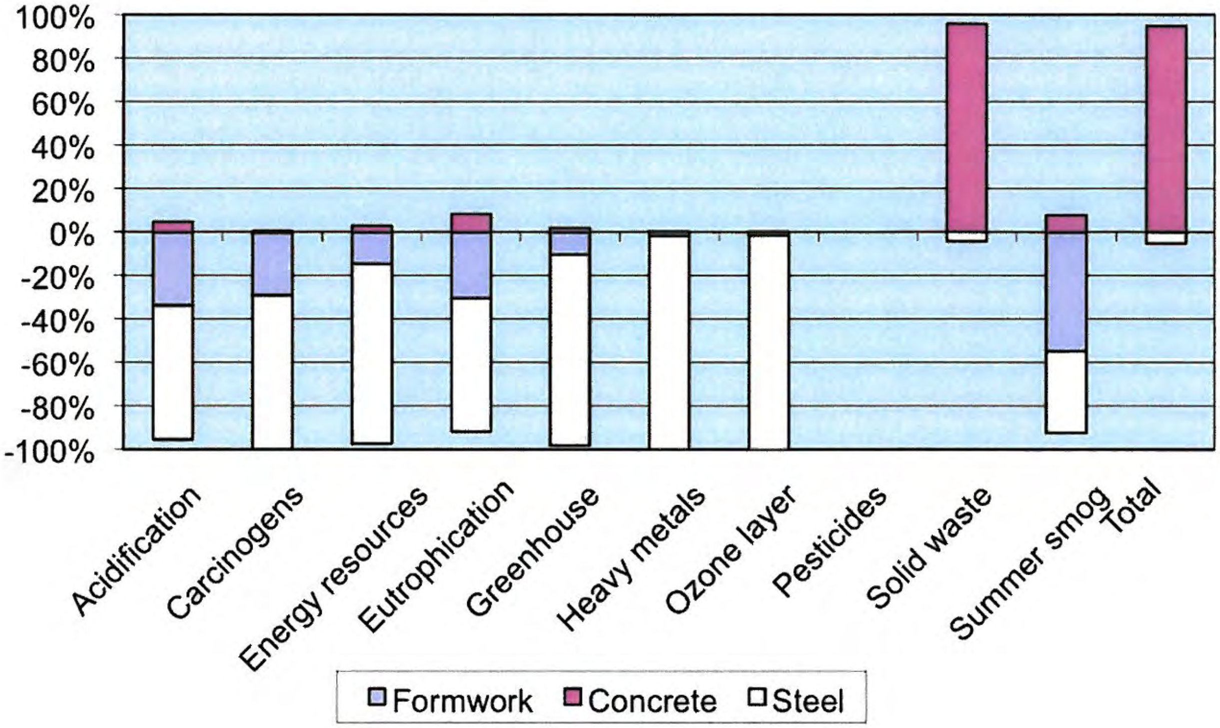


Exhibit 10: End-of-Life

Concrete Tank



FRP Tank

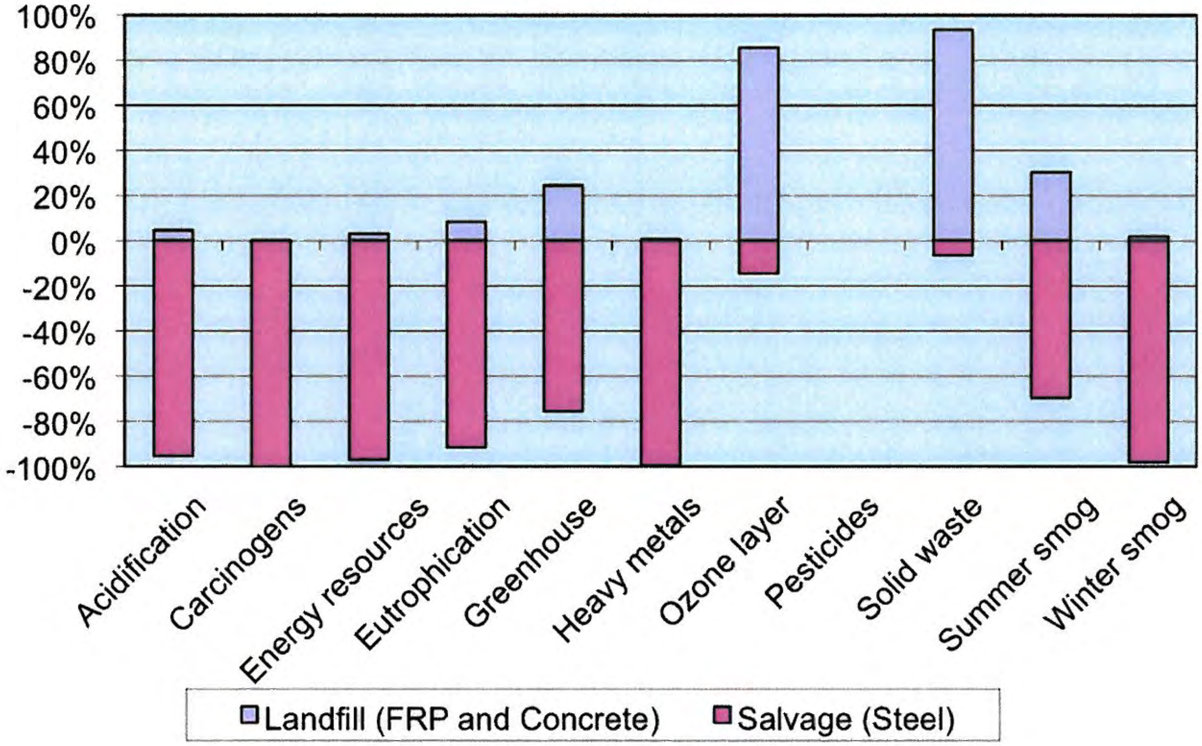


Exhibit 11: End-of-Life Comparision

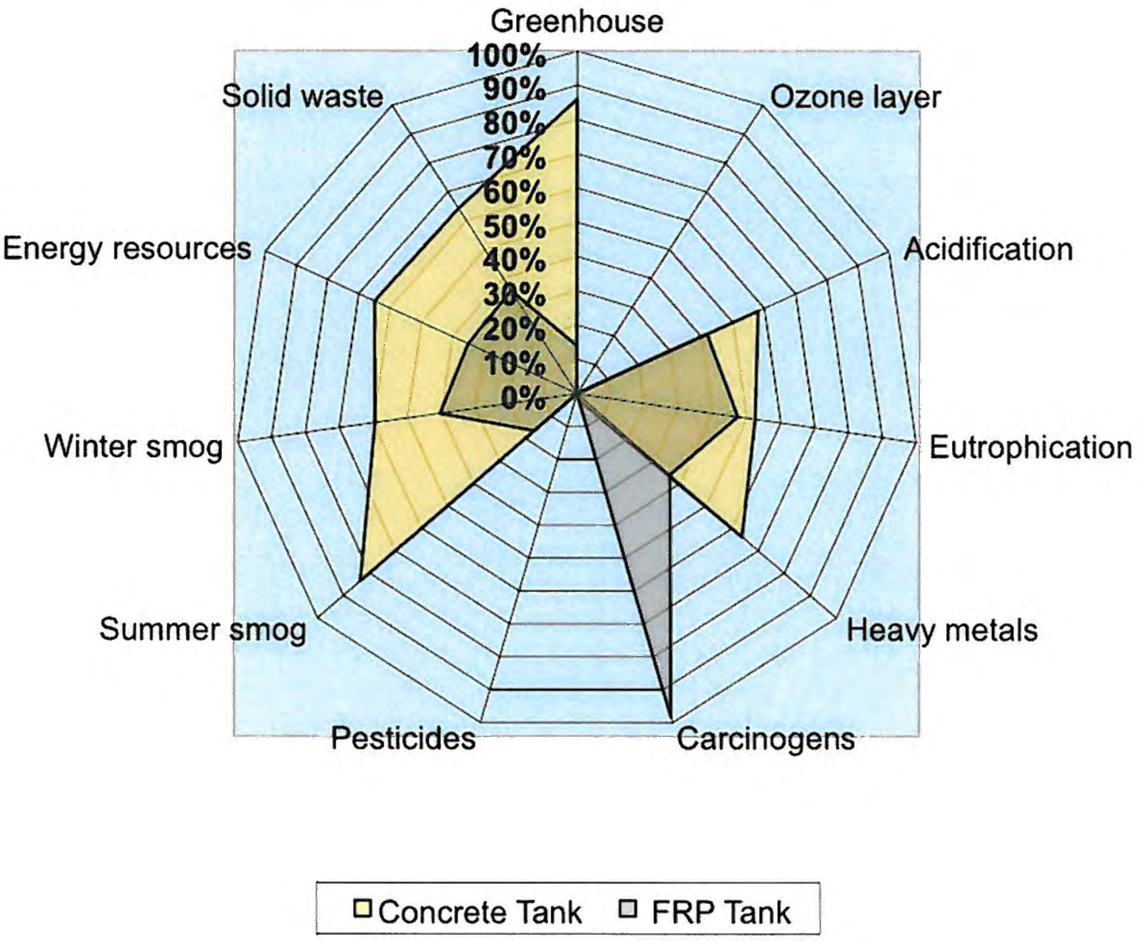
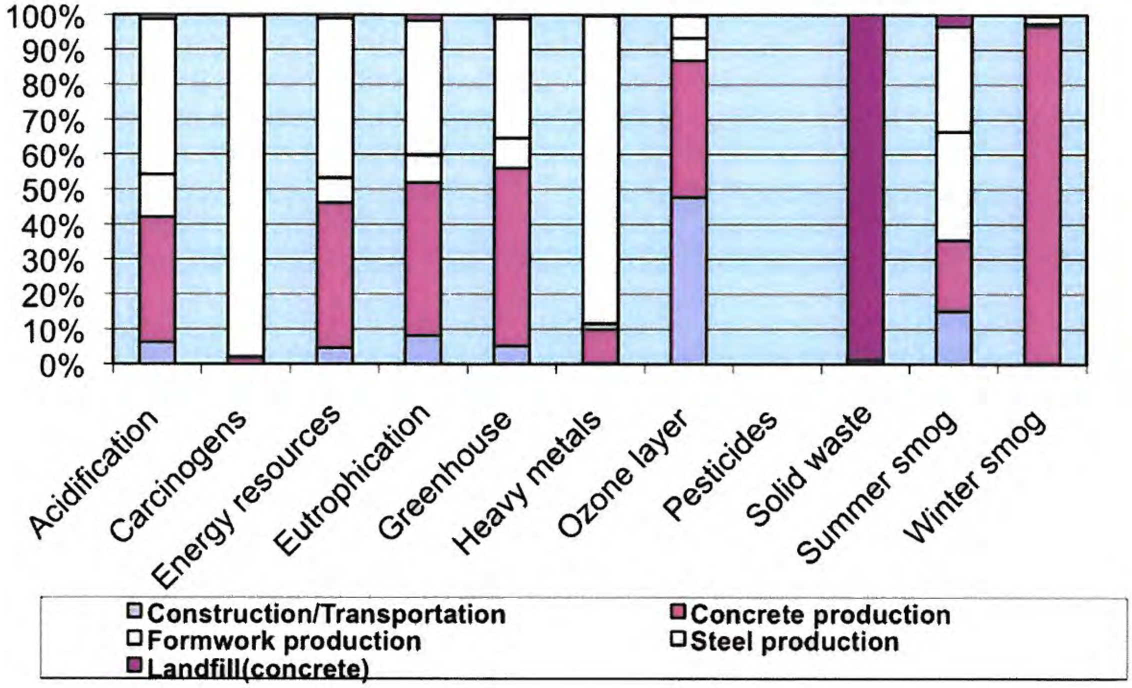


Exhibit 12: Total Life-Cycle Impact

Concrete Tank



FRP Tank

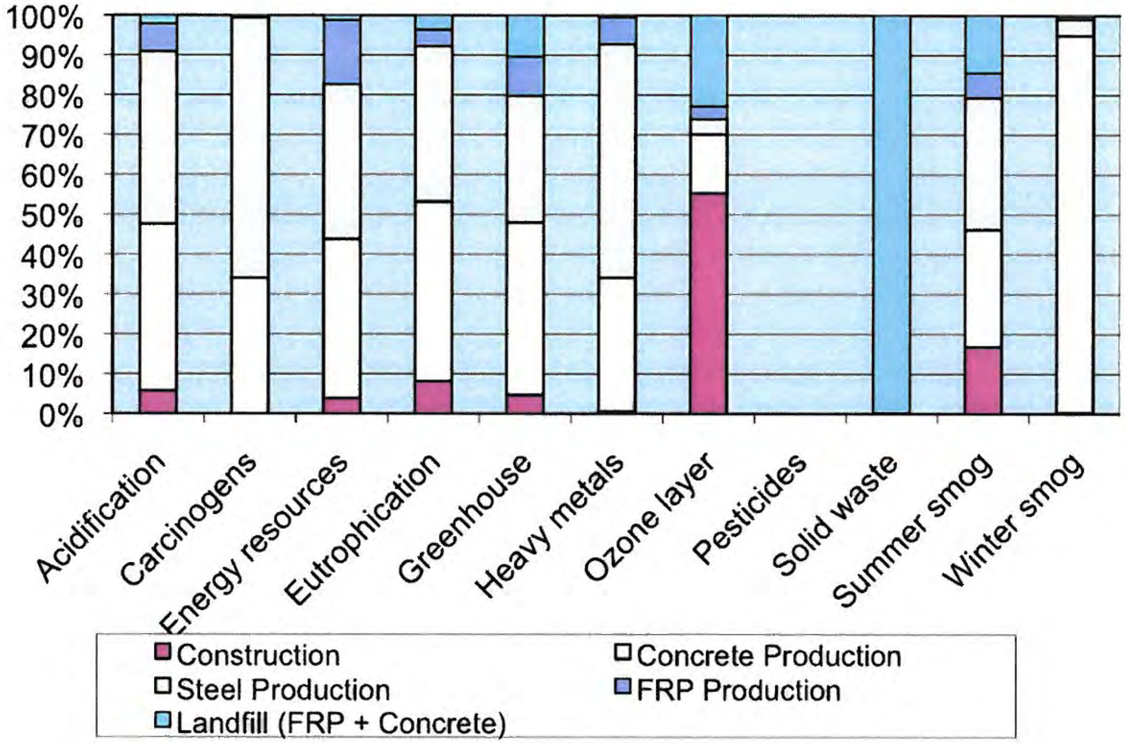


Exhibit 13: Total Life-Cycle Impact Comparision