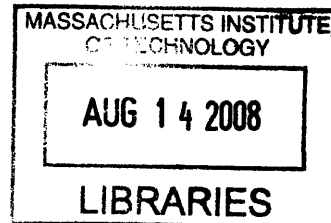


Environmental Impact of Various Kayak Core Materials

by

David R. Kirkland



SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN
PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF SCIENCE IN MECHANICAL ENGINEERING

AT THE

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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Submitted to the Department of Mechanical Engineering
on May 9, 2008 in Partial Fulfillment of the
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Mechanical Engineering

ABSTRACT

This thesis compares the environmental impact of fiberglass, Kevlar, carbon fiber, and cork. A kayak company is interested in using cork as a core material, and would like to claim that it is the most environmentally friendly of the four materials listed above. The efficacy of that claim is evaluated by modeling the manufacturing process, generating an input – output model and performing an exergy analysis.

The environmental impact of kayak core material construction on the over impact of kayak construction is nominal. Beyond that, the comparison of core materials results in a qualitative ranking from least to most impact, which is fiberglass, cork, carbon fiber then Kevlar.

The diversity of impact, from noxious gases, energy use, volatile liquids, land use and toxic wastes necessitates a qualitative analysis when full exergy data wasn't available. Because of this, the comparison was quantitatively based on the energy use and qualitatively based on each chemicals material safety data.

Thesis Supervisor: David R. Wallace

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Introduction to Kayaks

Kayaks are made from many different materials that cater to the whole range of skills, pocketbooks, and lifestyles. The functional requirements of different types of kayaking (ocean, river, racing, group etc) give rise to the need for many different materials. The different material properties are optimized to suit a specific type of kayaking. Despite the tailoring material selection isn't the only differentiating factor.

Cost plays a major role in selection of kayaks. The price range for kayaks is from \$20 to beyond \$5,000. A variety of factors influence a future kayak owner's decision to purchase, but price is generally dependant on means, expected use, and skill level. No matter the skill level or price range of prospective kayakers, the constant factor is that they expect to use there product in the great outdoors.

It may be assumed that because these people expect to use their product in the outdoors that they are also interested in preserving their ability to use both their product, and the outdoors, as long as possible. This assumption is the underpinning motivation to my research. No current kayak companies advertise their products as being especially environmentally friendly. Because customers lack the option of a selecting a kayak that is more conscious of its environmental impact (or footprint) they must select based on only the other two criterion. The extent to which environmental impact could influence a purchaser can be read about elsewhere; this thesis seeks to evaluate the environmental impact of four different kayak making materials.

High performance kayaks are presently made from Kevlar, carbon fiber, and fiberglass in an array of combinations. These materials, when used to create fiber reinforced plastic (FRP), are ideal for their high specific strength (strength to weight ratio). Another material that is being introduced into the kayak world, cork, is thought to have similar mechanical properties when ground up and agglomerated with a resin. These four materials are evaluated to determine what environmental impact each has.

Problem Statement

A company is interested in making kayaks with a cork core instead of fiber reinforced plastics. They wish to make two major claims about their product. The first is that the properties of cork will provide greater shock absorption and enhanced performance. The second is that cork core kayaks are more environmentally friendly than present technology. This thesis evaluates the efficacy of the second claim.

Four kayak core materials, Kevlar, carbon fiber, fiberglass, and agglomerated cork are evaluated in this thesis. The inputs and outputs of each step in the manufacturing process, for each core material, are listed. Flow charts depicting materials between processes are used to model each system and represent the boundaries of the analysis. A quantitative comparison of the chemicals, land use, work hours, energy use and other material use characterizes the overall footprint of each material with respect to kayak construction. An exergy analysis of each material is performed because direct comparison of chemicals is impossible, as each process has different solvents, initiators, resins etc.

The exergy analysis will be the first point of evaluation. The second point will be a more qualitative analysis based on the life cycle of the kayaks and the byproducts of manufacturing. The life cycle analysis compares acreage, energy use, gaseous emissions, chemical use, and chemical and solid waste.

Fiber Material Similarities and Overlap with Cork

The three fibers previously discussed, Kevlar, Carbon fiber, and fiberglass share many similarities. Diagram 1 below shows the processing stream for any of the fibers. Resins are used to bind the fibers together into a sheet. The selection of resins, as well as how the fibers are laid, impacts the mechanical and chemical properties of the overall material. The choice of resin is not material dependent, and for kayaks, epoxy is the most commonly used resin mix. Some other resins implemented in kayak construction are polyester and vinylester.

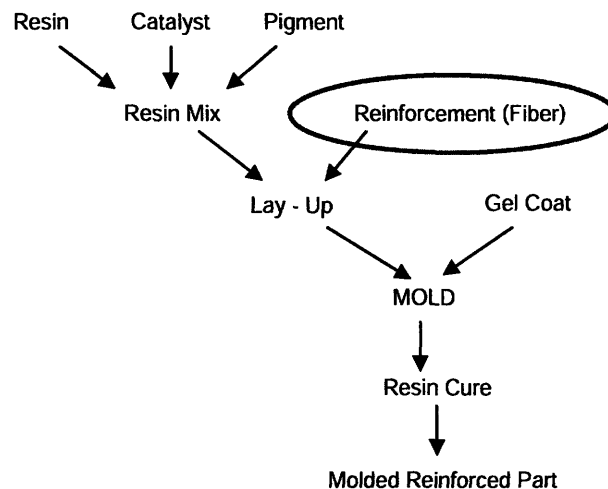


Diagram 1: General Procedure for Kayak construction from fiber, resin

Although epoxy is used with the fibers as a resin it isn't clear whether or not it would also be used as a binder to create agglomerated cork for kayaks. Many different resins are used for different purposes to create agglomerated cork, with epoxy being one of them. For the purpose of this study epoxy is assumed to be the resin of choice.

The construction of the hull shape following combination of the fiber and resin combination can be carried out in various ways. Some of the manufacturing methods are contact molding, vacuum bag molding, pressure bag molding, compression molding, matched die molding. Low scale production is almost always done by hand (contact molding), which is how I believe the cork would be formed. Both fabrics (woven cloth) and chopped fiber (short fibers in a resin matrix) can and are implemented in kayak construction. Fabrics are used in the higher end kayaks, and more often overall; it will be used in this paper for all the fiber types. All kayaks require an external coating for impact resistance, sun protection, and corrosive resistance, which is applied to the lining of the mold and allowed to set to a gel consistency before the fiber resin mix is added.

For the common practices (outside red oval) of the kayak construction there are many energy and material costs. Table 1 shows a typical inputs and outputs of that stage in the process. This extensive list and gives perspective on the

Table 1: Input / Output List for a part of the kayak making process that is not unique to any of the core materials [1]

Input	Output
Cleaning cloths for equipment and mold	Solvent or resin laden cleaning cloths
Mold release agents-wax or polymer based	Spent or residual mold release agents
Gel coatings	Solvated and residual resins, wasted gel
Vapor suppressants	Scrap waste from trimming
Emulsifiers	Air – styrene, toluene, dimethylphthalate, volatile organic compounds and air pollutants from solvents, catalysts, resins, foams, paints, etc
Inert fillers	Surplus waste, and or expired chemicals
Foaming agents (polyester based)	Overspray solids
Adhesives	Spent Solvents and still bottoms
Solvents (acetone, toluene, xylene, etc)	Spent Filters
Styrene – solvent, and co-reactant	
Initiators and catalyst	
Solvated resins	
Energy	
Paints and thinners	

overall environmental impact of kayak construction. Understanding the percent impact of varying the core material, although unimportant in determining the absolutely “most environmentally friendly core material” it is necessary in qualitatively understanding the scope of the study. If it turns out that all the other steps (in making the resin, molds, shipping, chemicals, etc) are by far the greater impacts on the environment, then it becomes only a technicality to call the kayak with the most environmentally friendly core material the “most environmentally friendly kayak”. This thesis will not do a detailed comparison of the overall kayak footprint.

The use of similar resins and manufacturing processes for everything outside of the red oval (Diagram 1) allow the boundary of the analysis to be drawn around the core material construction itself. This is contingent on the assumption that all kayak types use the same amount of resin, which is valid at least for the fibers. Another necessary assumption is that the weight of material is the factor that is held constant for all kayak types. This gives rise to a direct comparison of impact per unit weight.

Only the immediate precursors for the polymers were considered in the environmental impact model. This results in a bias towards the fibers because it neglects the processes necessary to create those chemicals, and their precursors etc. The environmental footprint will look smaller for the 3 fibers. This simplification was used because in most cases the precursor chemicals are bi-products of other manufacturing processes. As such, they are considered “external” to the process.

Kevlar Manufacturing

Kevlar Overview

The needs for strong, highly thermally resistant, materials funded research in the field of polymers. Exploration into spinning aromatic polyamides (a type of polymer) into fibers led to the discovery of a fiber which today carries the brand name of Kevlar. Kevlar has a very high modulus of elasticity, while also having a very high strength. By creating a woven fabric, Kevlar became immediately useful for police, firefighting, and military applications. As the costs came down Kevlar has begun to be implemented in recreational products, and anything that needs to be either “puncture proof and fracture proof” [2].

Kevlar has different levels of refinement for different purposes. Kevlar 29 is used for ropes, cables and protective clothing. Kevlar 49 has half the elongation and twice the modulus of Kevlar 29 and is used primarily to reinforce plastic. Kevlar 49 can be processed further into Kevlar 149 which is used to reinforce composites for aircraft components [5]. Kevlar 49 is the material used in kayaks and will be the material reviewed here.

Overview of Process

Aromatic polyamides (which Kevlar is) can be synthesized by a low temperature condensation reaction of an amine group and a carboxylic acid halide group [3]. An initiator for the reaction is needed for the polymerization (chaining) of the molecules to occur. The initiator is comprised of two different chemicals, one to act as a co-solvent with and ionic component to occupy the hydrogen bonds of the amide group, and the other to dissolve the aromatic polymer. After the polymerization reaction a highly viscous semisolid, called the intermediate is formed.

To draw the intermediate it must be made into a liquid. A new solvent, sulfuric acid is added to the intermediate to make it into a liquid. Sulfuric acid is considered the spinning solvent. The new material, a complex, is made by heating the sulfuric acid – intermediate solution. The complex is then drawn using spinnerets. Spinning the material through an air gap into the quenching water produces perfectly aligned polymer chains. After the first spinning Kevlar 29 is produced. A second cycle of drawing, at a higher temperature alters molecular structure, creating Kevlar 49. A representation of the chemical reaction that results in the polymer chain is shown in Figure 2.

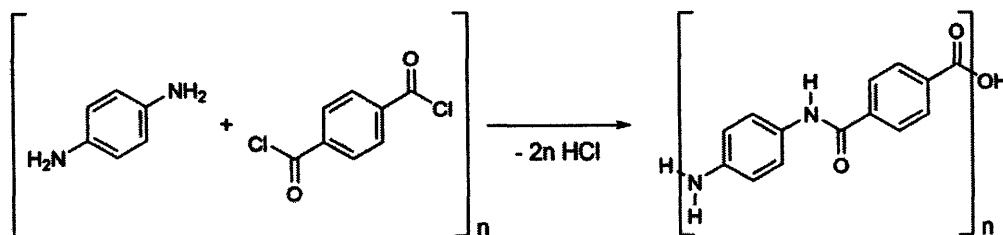
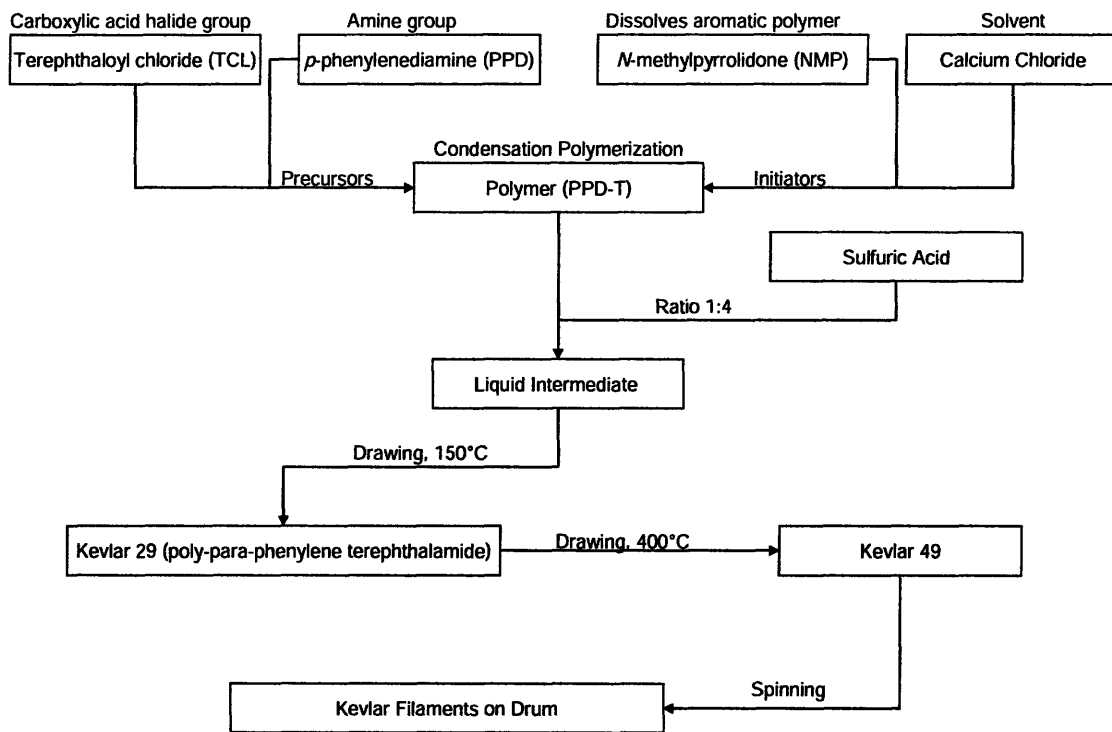


Figure 2: Kevlar Polymerization via condensation polymerization reaction

Detailed Flow of Materials and Energy



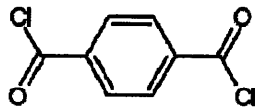
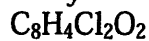
[4]

Input Output Model

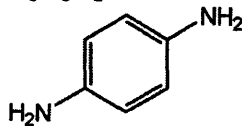
Input

Polymerization

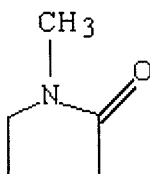
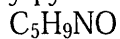
Terephthaloyl chloride (TCL): 1 mole



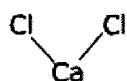
p-phenylenediamine (PPD): 1 mole



N-methylpyrrolidone (NMP): 1 mole

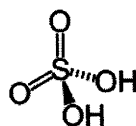


Calcium Chloride: 1 mole



Intermediate

Sulfuric Acid: 4 moles



Kevlar

Energy: $500kJ/cm^3$
 $0.72GJ/kg$

Output

Polymerization

Hydrochloric acid: 2 moles



Intermediate

Spent Sulfuric Acid: 4 moles

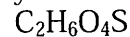
Sulfuric Acid 92%



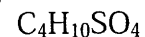
Distillates (petroleum), alkylate 7.5%

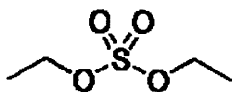
Alkylate petrol XXXX

Dimethyl Sulfate 0.2%



Diethyl Sulfate 0.2%



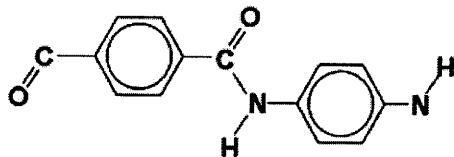


[6]

Spinning

Kevlar 1 mole

$C_{14}H_{12}O_2N_2$



Carbon Fiber Manufacturing

Carbon Fiber Summary

Carbon Fibers are extensively used for their high specific strength, which means that they have a high strength to weight ratio [8]. The high cost of manufacturing, combined with its performance as a core material combine to make a high end kayak.

Carbon fiber refers to fibers which are at least 92 wt. % carbon in composition [7]. Their structure can be crystalline, amorphous, or partly crystalline. The functional requirements of the consumer dictate which type of carbon fiber to use, which in turn determines what type of manufacturing process to use.

Carbon fiber reinforced plastics (CFRP) are becoming pervasive in recreational equipment as science continues enhancing equipment. Carbon fiber kayaks use a mixture of carbon fiber, resin and plastic in combination to create a CFRP kayak.

Carbon fibers are fabricated using polymer fibers (e.g. polyacrylonitrile), carbonaceous gasses, or petroleum pitch derived from oil processing [10]. Only the polyacrylonitrile (PAN) and pitch based carbons are implemented in kayaks. The carbon fiber made from pitch is more graphitizable than Pan, which increases the stiffness of the resulting fiber. Despite this fact, PAN is more often used as the precursor material in the construction of kayaks because it has a higher inherent tensile strength, as well as a lower modulus of elasticity, making it stiffer (a desirable trait in kayaks).

Overview of Process

Table 2 shows a brief overview of the process flow for each of the starting materials.

Pan	Pitch
Polymerization	Pitch Preparation (isotropic/anisotropic)
Wet Spinning	Melt Spinning
Stabilization	Infusibilization
<i>Oxidizing atm.</i>	<i>Oxidizing atm.</i>
Carbonization	Carbonization
<i>Inert atm.</i>	<i>Inert atm.</i>
Graphitization	Graphitization
<i>Inert atm.</i>	<i>Inert atm.</i>

Table 2: Processing Stream for both major precursor materials [9]

The process examined in detail in this research is that for the Pan precursor. Much like Kevlar, the process begins with creating a polymer. The polymer PAN can be made in various ways, but aqueous dispersion polymerization is used most often in industry [7]. De-ionized water is the medium in which all reactions take place. Iron is reduced to make a free radical out of bisulfate. The free radical then breaks a bond in the acrylonitrile, allowing it to polymerize. EDTA, an acid, binds with the iron to stop polymerization. Everything but the polymer is then filtered. Figure 3 shows the chemical structure of a mer group of PAN.

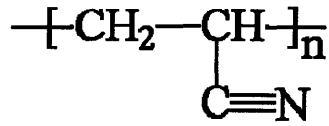
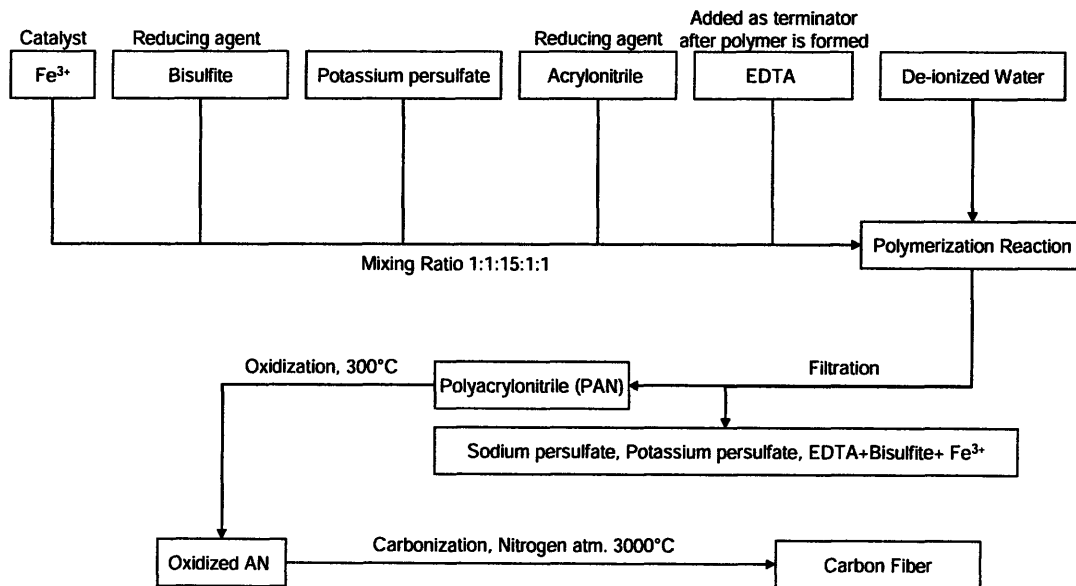


Figure 3: Polyacrylonitrile (PAN), $\text{C}_3\text{H}_3\text{N}$, polymer precursor of carbon fiber

The polymer is then turned into a liquid with a solvent, and transferred to a container with hundreds to thousands of spinnerets on it. The processing of the polymer then proceeds in four continuous stages. The filaments are then drawn through the holes onto a spindle. The filaments are directly fed to the stabilization stage of the manufacturing process. During this stage the filaments are heated to 300°C , oxidizing the PAN. This material is sometimes sold for its capability as a fireproofing material. The filaments are then directly fed to an inert environment (gas) environment where they are heated to around 3000°C for optimal carbonization. Carbonization begins to occur at 1000°C and becomes more and more severe until it is nearly 100% carbonized at 3000°C . The modulus starts low when it begins carbonizing, and increases with temperature. When the temperature approaches the higher end, carbonization is also considered graphitization due to the crystalline structure.

Detailed Flow of Materials

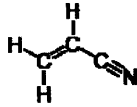
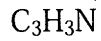


Input Output Model

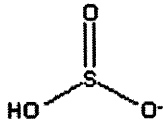
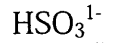
Input

Polymer Precursor

Acrylonitrile (AN): 1 mole



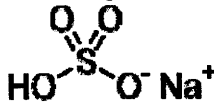
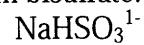
Bisulfite: 1 mole



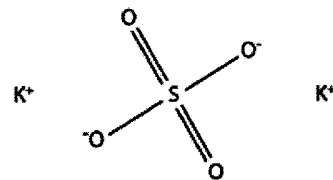
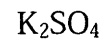
Iron: 1 mole



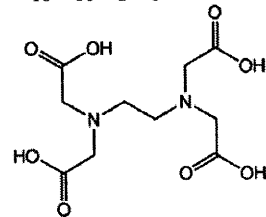
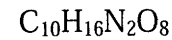
Sodium bisulfate: 1mole



Potassium sulfate: 15 moles



EDTA: 1 moles



Clean Filter for extracting polymer

Oxidation, Carbonization

Energy: 30MJ/kg

N_2

Output

Polymerization Reaction

Sodium bisulfite + EDTA + Fe: 1 mole

Sodium persulfate: 1mole

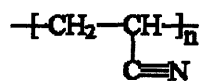
Same as input

Potassium persulfate: 1 mole

Same as input

Carbon fiber

C_3H_3N



Used Filter

Oxidation, Carbonization

Nitrogen gas

N_2

Fiberglass Manufacturing

Fiberglass Overview

Fiberglass is made from very thin fibers and is almost always implemented in products as a reinforcing material. The fiberglass and the composite materials that result from adding resins have many diverse applications in industry and art. Common uses are insulation, reinforcement, heat/corrosion resistant fabrics, strong fabrics, and sound proofing.

Silica (SiO_2) is the primary material used in fabrication of fiberglass. But, like any glass production, requires a high operating temperature for production. To combat this other chemicals are used to increase the workability of the material.

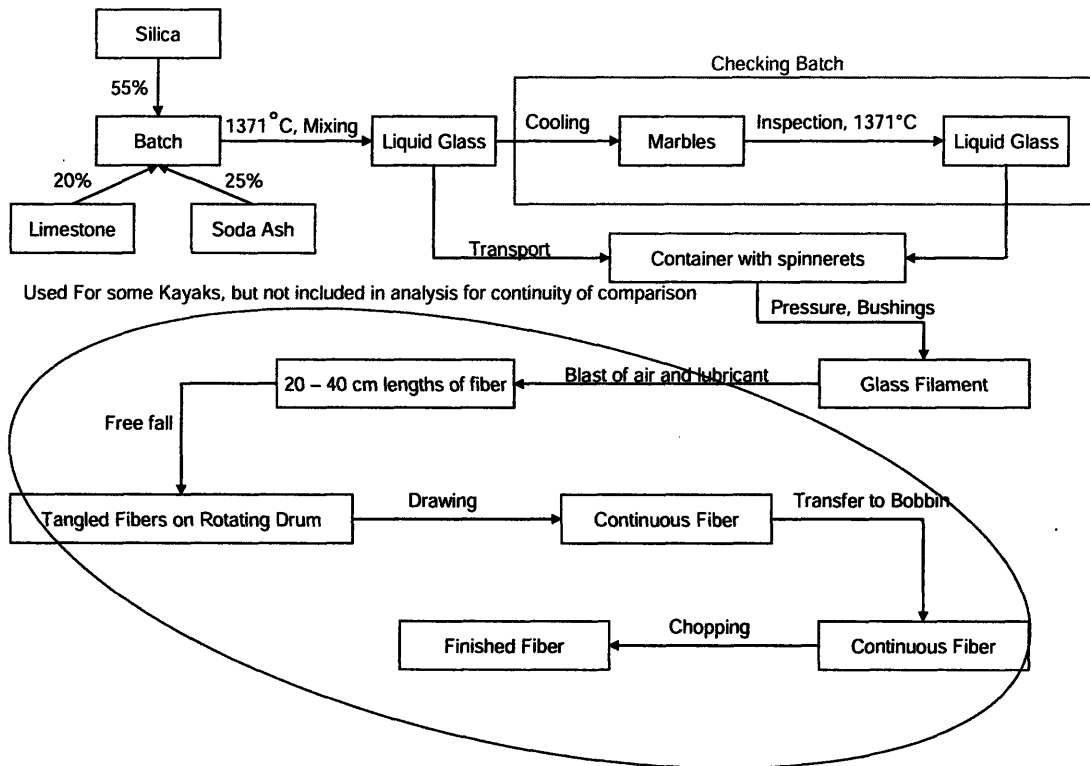
Fiberglass, despite being drawn through very small holes, remains an amorphous solid. The fibers are used like thread, and can be woven into fabrics. They are also sometimes chopped into shorter lengths to create an even consistency, fluffy, wool like, material.

Overview of Process

Three main materials are used in the fabrication of fiberglass: Silica sand, limestone (for the calcium carbonate that is naturally occurring, but also has dolomite), and soda ash[11]. Silica sand is the primary glass, with limestone or soda ash mixed in to decrease the melting point. The melted glass is transferred to a container with anywhere from 200 to 3,000 holes in it. These holes are coated with a platinum/rhodium alloy that naturally wets the surface, allowing free flow of the glass.

Two main production types can occur from here. One creates long thread, while the other creates staple fiber (20-40 cm lengths) of fiberglass. For kayak manufacturing both the staple fiber and fiberglass woven fabric is used. The staple fiber can be sprayed onto a mold, or manipulated like a liquid. The full process, is shown below, but only the fabric form will be carried through to the analysis.

Detailed Flow of Materials

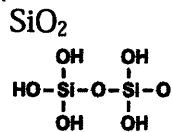


Input Output Model

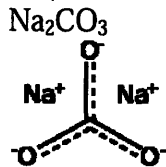
Input

Batch

Silica (Silicon Dioxide) 55% by weight

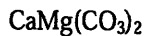


Soda Ash (Sodium Carbonate) 25% by weight



Limestone 20 % by weight: equal parts

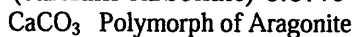
Dolomite 6.67%



Aragonite (calcium carbonate) 6.67%



Calcite (calcium carbonate) 6.67%



[12],[13]

Melting / Mixing
Energy to melt:

$$Cp_{glass} = .84 \frac{\text{Joules}}{\text{gm} \cdot \text{Kelvin}}$$

$$E = .84 \frac{J}{\text{gm} \cdot K} \cdot \frac{1000 g}{kg} \cdot \frac{(1375 - 25)K}{1} = 1.134 \frac{MJ}{kg}$$

Checking Batch
Energy to melt
1% of batch = 11.34 KJ

Output
Spinning Fiber
Fiberglass
(SiO₂)_n

Cork Manufacturing

Cork Summary

Cork trees have been grown for their bark for thousands of years. The properties of cork make it useful as insulation, sound proofing, padding, buoy, life vests, bottle stoppers, etc. Cork is mainly harvested around the Mediterranean because the local climate lends itself to high outputs.

Cork is the bark of the Cork Oak (*Quercus Suber*) tree. Trees are ready for their first harvest after 25 years. Every nine years following the first harvest the tree is again ready to be stripped of its bark. The first two harvests have minimal commercial value, as the grade of cork is very low. The trunk and larger branches are stripped every 9 years. The process of stripping the tree motivates, rather than stunts the growth of the tree. Every year the tree adds a layer of cells to the innermost and outermost parts of the tree, increasing the root diameter, and the thickness of the bark [14]. The average lifespan of a tree is 170 years, yielding around 16 harvests during its lifespan. The amount of cork per harvest varies greatly, depending on age and size.

Overview of Process

Cork oak trees are cultivated by clearing the ground of undergrowth, regularly pruning, and tilling of the soil. The cork is removed from the trees by cutting into the deepest natural indentations and stripping away the bark in sheets. After stripping the cork from the tree the strips are stacked and allowed to season for 6 months in a sheltered environment.

The strips are then boiled to remove organic solids and enhance the mechanical properties of the cork [15]. After stabilizing (reaching optimal moisture content) the planks are stacked and sorted based on porosity, thickness, and appearance.

The majority of cork is used to produce bottle stoppers, but various other applications use sheet cork. The leftovers from punching and forming those other products are referred to scrap cork. The scrap cork is the cork that is used for kayak manufacture. The following process will diverge from the other products and look only at the scrap cork.

The leftovers are pulverized to create homogeneously sized pieces. The granules are then used in many different products. Again the Kayak application will be followed. The granules are layered to a predetermined thickness of and "glued" together with a resin. In this form it is considered agglomerated cork. The agglomerated cork can be designed to have any shape or thickness by using various manufacturing techniques. The mechanical properties can also be engineered through selection of geometry and resin.

Definition of Boundaries

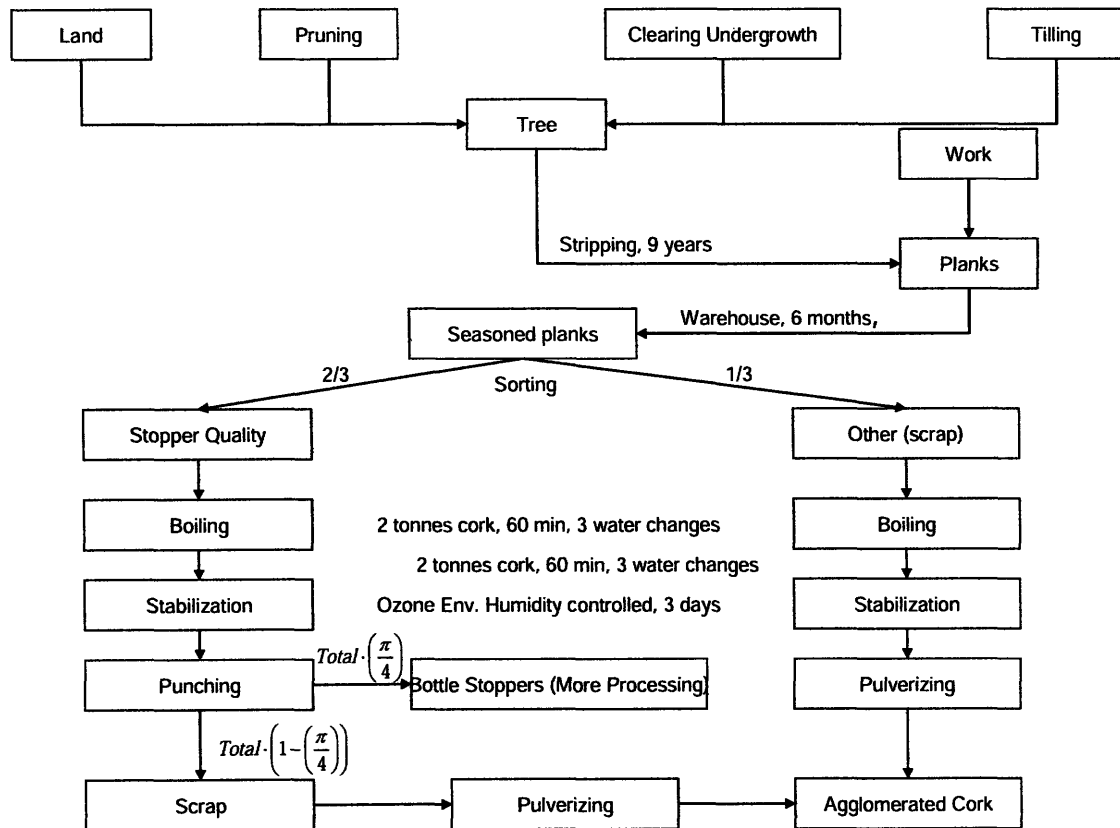
This study separates the manufacturing process into two sections: Cultivation to scrap cork, and scrap cork to agglomerated cork as a formed kayak core.

The first part of the manufacturing process will be analyzed in its entirety and multiplied by the fraction of cork that becomes agglomerated cork. The process of

cutting out corks, the scraps of which are the agglomerated cork, will be left out because it will be assumed that the entirety of the cork *could* be pulverized via the next step in the manufacturing process.

The second part of the manufacturing process will include the materials for creation of the core material, but not the actual forming process, as this is highly variable and similar across all the different materials.

Detailed Flow of Materials



Input Output Model

Input

Cultivation

Trees per acre:

Avg distance between trees = 8m

[16]

64m²/tree

156 trees/hectare

150kg/tree (avg over lifespan)

2600kg/(hectare*year)

Work Hours

Pruning: Once / year = 4hrs/tree/year

Tilling: Once / year = .33hrs/tree/year
 Clearing Shrubs: Twice / year = 1hr/tree/year

Collection

Cutting

Hours: 16 hrs / harvest = 1.78hrs/tree/year

Transportation

Hours: 4 hrs/year/tree
 250 kW operating vehicle
 Energy: 3.6 GJ

Seasoning

Storage

Time 6 months

Sorting

2/3 harvest of high enough quality to produce cork stoppers
 1/3 to become agglomerated

Boiling

2000 kg of cork per batch
 60 min cycle, 12.5m³ volume per batch
 2000kg at 240kg/m³ = 8.33m³ of cork
 3 water changes at 4.16m³ / change
 Energy (100-25)°C*12.5m³*4,184kJ/(m³ K) = 3.92 GJ
 Volatile Compound Trap – removes all volatiles from water

Stabilization

Controlled environment, humidity, 3 days
 Ozone in environment

Punching

Leftover (modeled as tangent cylinders)

$$Scrap_Cork = Total \cdot \frac{2}{3} \cdot \left(1 - \left(\frac{\pi}{4}\right)\right)$$

Output

Punching leftovers and low quality

Pulverize cork

$$Scrap_Cork + Low_Quality = Total \cdot \frac{2}{3} \cdot \left(1 - \left(\frac{\pi}{4}\right)\right) + \frac{1}{3} \approx Total \cdot .476$$

Input/Output of Each Core Material

	Kevlar	Quantity	Molar Mass [g/mole]	Amount (in g) to make 1 g of core material
Input	-C ₈ H ₄ Cl ₂ O ₂	1 mole	203.024	.845
	-C ₆ H ₈ N ₂	1 mole	108.134	.450
	-C ₅ H ₉ NO	1 mole	99.133	.413
	-CaCl ₂	1 mole	110.976	.461
	-H ₂ SO ₄	4 moles	98.979	1.647
	- Energy	.72GJ/kg		
Output	-HCL	2 moles	36.461	.303
	-H ₂ SO ₄	3.68 moles	98.979	1.516
	-Alkylate petrol	.3 moles		
	- C ₂ H ₆ O ₄ S	.08 moles	126.133	.042
	- C ₄ H ₁₀ SO ₄	.08 moles	154.187	.051
	- C ₁₄ H ₁₂ O ₂ N ₂	1 mole	240.262	1.00

	Carbon Fiber	Quantity	Molar Mass [g/mole]	Amount (in g) to make 1 g of core material
Input	- C ₃ H ₃ N	1 mole	54.064	1.00
	- HSO ₃ ¹⁻	1 mole	81.072	1.50
	- Fe ³⁺	1 mole	55.847	1.03
	- NaHSO ₃ ¹⁻	1 mole	104.062	1.92
	- K ₂ SO ₄	15 moles	174.260	48.3
	- C ₁₀ H ₁₆ N ₂ O ₈	1 mole	292.246	5.40
	- Clean Filter	1 unit		
	- Energy	30MJ/kg		
Output	- NaHSO ₃ ¹⁻	1 mole	104.062	1.92
	- K ₂ SO ₄	1 mole	174.260	48.3
	- C ₁₀ H ₁₆ N ₂ O ₈ ⁺	1 mole	540.859	10.0
	Fe ³⁺ + HSO ₃ ¹⁻			
	- C ₃ H ₃ N	1 mole	54.064	1.00

	Fiberglass	Quantity	Molar Mass [g/m]	Amount (in g) to make 1 g of core material
Input	- SiO ₂	1 moles	60.084	1.00
	- Na ₂ CO ₃	.455 moles	105.989	.802
	- CaMg(CO ₃) ₂	.121 moles	184.401	.371
	- CaCO ₃	.121 moles	100.087	.202
	- CaCO ₃	.121 moles	100.087	.202
	- Energy	1.145 MJ/kg	N/A	
Output	- (SiO ₂) _n	1 mole	60.084	1.00

	Cork	Quantity per tree per year	Amount (in g) to make 1 kg of core material
Input	- Land - Work Hours - Energy - Water - Ozone	64 m ² 11 hrs 7.5 GJ/kg 12.5 m ³	8.07 m ² 1.39 hrs 94.5 KJ 1.58 m ³
Output	- Cork	7.93kg/year*	1 kg

*agglomerated cork

Energy Input for Each Material

	Fiberglass	Cork	Kevlar	Carbon Fiber
Energy	1.145 MJ/kg	7.5 GJ/kg	.72GJ/kg	30MJ/kg

The input – output model is a helpful in looking at the quantities of different materials used in the manufacturing process. It does not, however, tell us whether water or calcium chloride should be deemed worse or better for the environment than, say, hydrochloric acid. Material safety data sheets are available for all the chemicals listed above. They are extensive and outline what types of hazards each chemical presents. These, as with land and work hours are difficult to compare directly. They are easily searchable, and have been reviewed for a qualitative understanding of all of the chemicals above [17]. They were not included in this report because they can be found online, and are even more subjective than the other evaluation methods employed in this paper.

Energy for manufacturing of each material is listed as energy per kg produced. This figure may be misleading, as this paper is comparing the core material environmental impact per kayak. It is likely that since cork is much less dense than the fibers, it will use around four times less material (by weight) per kayak than the other materials, greatly reducing the relative impact per kayak. The other three materials have similar densities, resulting in similar energy use.

Exergy of Materials

Kevlar		Exergy
-C ₈ H ₄ Cl ₂ O ₂	Terephthaloyl chloride	
-C ₆ H ₈ N ₂	<i>p</i> -phenylenediamine	
-C ₅ H ₉ NO	<i>N</i> -methylpyrrolidone	
-CaCl ₂	Calcium Chloride	87.9
-H ₂ SO ₄	Sulfuric Acid	163.4
-HCL	Hydrochloric acid	84.5
-H ₂ SO ₄	Sulfuric Acid	87.9
-Alkylate petrol		
- C ₂ H ₆ O ₄ S	Dimethyl Sulfate	
- C ₄ H ₁₀ SO ₄	Diethyl Sulfate	
- C ₁₄ H ₁₂ O ₂ N ₂	Kevlar	

Carbon Fiber		Exergy KJ/mol
- C ₃ H ₃ N	Acrylonitrile	9035 btu/lb
- HSO ₃ ¹⁻	Bisulfate	
- Fe ³⁺	Iron	376.4
- NaHSO ₃ ¹⁻	Sodium Bisulfate	
- K ₂ SO ₄	Potassium Sulfate	35.0
- C ₁₀ H ₁₆ N ₂ O ₈	EDTA	
- NaHSO ₃ ¹⁻	Sodium Bisulfate	
- K ₂ SO ₄	Potassium Sulfate	35.0
- C ₁₀ H ₁₆ N ₂ O ₈ + Fe ³⁺ + HSO ₃ ¹⁻	Combination	

Fiberglass		Exergy KJ/mol
- SiO ₂	Silicon Dioxide	7.9
- Na ₂ CO ₃	Sodium Carbonate	41.5
- CaMg(CO ₃) ₂	Dolomite	15.1
- CaCO ₃	Aragonite	1.0
- (SiO ₂) _n	Silicon Dioxide	2.0

The exergy of all of the materials was not calculated because Gibb's free energy (needed for calculation) for some of them wasn't available. Cork was not included in the exergy analysis as very few chemicals are used in the fabrication process.

Conclusion

Scope of Study

This thesis outlined the manufacturing process of Kevlar, carbon fiber, fiberglass and agglomerated cork. An input output model based on the different steps of the manufacturing process depicted material usage and byproducts.

The exergy analysis wasn't able to be fully completed as data for Gibb's free energy wasn't available for some of the more obscure chemicals. Even if it had been completed it wouldn't have contributed to the purpose of this paper, which is to evaluate whether or not cork is most environmentally friendly of the materials. It wouldn't have contributed because many of the contributors to footprint for cork are inaccessible with an exergy analysis. It would, however, have helped rank the impact of the fibers.

All of the fibers have very similar resin use with respect to quantity and type. The usage by cork wasn't available, but I suspect it would be significantly different in quantity, if not in type as well.

Evaluation of Claim

To be able to claim the most environmentally friendly core material would be quite a stretch. Ultimately, comparing land use, human work etc with chemical processes and exergy is, to be hackneyed, like comparing apples to oranges. Despite qualitative and quantitative understanding of the process it is ultimately a value system to deem one of the processes better or worse. There are several standardized systems that define different value systems, and within the scientific community they are used to compare these disparate impacts.

The environmental footprint of a high end kayak is quite large. The core material production is a small fraction of that larger process. Parsing out the variation within the small section of the process is helpful, but by no means the full picture. Small variations in the mechanical property specifications would result in shifts large enough to "drown out" any "winner" of the best for the environment contest. By looking at the material safety reports for each of the chemicals, and also considering the energy of production, the fibers should be ranked from fiberglass to carbon fiber to Kevlar, with fiberglass being the best for the environment and Kevlar being the worst. By comparing Fiberglass with cork production, both have negligible waste, but very different inputs. The land use compared to the energy consumption leads me to believe that fiberglass could be made more sustainable. If energy was harvested from the same amount of land as required by cork, the energy to make an equivalent amount of fiberglass would be produced. The overall ranking then is fiberglass, cork, carbon fiber, and then Kevlar.

Further Study

Machine specifications from manufacturers would make more accurate energy calculations. Deriving energy use from theoretical understanding of the process may bias one material over another. Tracking materials backward and following every branch as far as it goes (until primary materials are found) would be very informative.

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