VANGUARD

UNIVERSITY OF
MASSACHUSETTS
LOWELL

2014

Concrete Canoe Design Paper

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EXECUTIVE SUMMARY

The University of Massachusetts Lowell (UMass Lowell) prepares its engineering graduates with the knowledge and life skills needed to excel in their careers. In the past year UMass Lowell has gained national recognition for its education, including being named the "Most Underrated College in America" by Business Insider (June 2013). As the university rises in the ranks, so follows the UMass Lowell concrete canoe team.

UMass Lowell's first appearance at the National Concrete Canoe Competition (NCCC) was in 1994 with a first place victory at the New England Regional Competition (NERC) with their canoe *The Titanic*. In the last three years the concrete canoe team at UMass Lowell has climbed the ranks in the NERC—placing 3rd with *Green Monster* in 2011, 2nd with *Revolution* in 2012, and finally earning 1st place with *Moswetuset* in 2013 for the first time since *The Titanic*. The 2012 and 2013 experiences at the NCCC inspired new and innovative ideas for the upcoming 2014 season.

Steampunk romanticizes Victorian-style modern machinery that run entirely on steam and mechanical works. It symbolizes the exploration of innovation by pushing the limits of functionality and creativity. The 2014 UMass Lowell concrete canoe team embraced the steampunk spirit—experimenting with new techniques and innovations throughout the process.

The 2014 season started with the design and construction of a practice canoe, *McPortland*, by reusing materials from *Moswetuset*. The hull for *McPortland* was determined using an iterative design process and the concrete used *Revolution's* mix as a baseline for strength. The final hull specifications (Table 1) incorporated paddler feedback from *McPortland*. Analysis identified three high stress zones along the canoe caused by different loading cases for the structural elements, bulkheads, and hull. A post tensioning system (PTS) was also researched and implemented this year which will provide a basis for PTS design in future canoes.

The mix design team researched the chemistry behind cement hydration and discovered that limiting the hydrated lime content was the key to creating a strong concrete mix with low unit weight. Three different mixes with deformational compatibility were developed for optimal placement and strength requirements, and a pre-cast mix was developed for aesthetic purposes (Table 2).

The construction team invested time into exploring multiple construction techniques. Inspired by the idea of steampunk and advancing the concrete curing process, the team used heat transfer theories to develop a "coolant core" that would ensure a complete wet cure of the canoe. This was combined with the design of a hydration chamber, which resulted in an optimal curing environment. New mold inlays and outlays were created as aesthetic elements of the canoe. The team was also challenged by the introduction of the PTS and how to tension the tendons without affecting the canoe's structural integrity.

With the amount of research and innovation dedicated to the 2014 season, management and communication were crucial to successfully complete the project. The team was able to work together to decide which new ideas to invest in while keeping within the project budget. The addition of a field manager improved quality control and construction methods, and allowed the project manager to focus on budget, material procurement, and community outreach.

The advancements achieved by UMass Lowell's 2014 concrete canoe team will benefit the team in future seasons. It is with that spirit that UMass Lowell is proud to present *Vanguard,* a leader in innovation and research, for the New England Regional Competition.

Table 1: *Vanguard* Specifications

Estimated Weight	115 lb
Length	20.5 ft
Maximum Beam	27.8 in
Depth	12.9 in
Thickness	3/8 in
Primary Colors	Silver and Black
Reinforcement	Fiberglass Mesh Carbon Fiber Mesh Galvanized Steel Braided Wire

Table 2: *Vanguard* Concrete Properties

Concrete Properties	Structural	Hull	Bulkhead	Pre-cast
Plastic Unit Weight (pcf)	42.3	34.8	37.3	53.7
Oven-dried Unit Weight (pcf)	41.1	33.8	35.6	52.0
28-day Compressive Strength (psi)	1,158	729	874	2,300
28-day Tensile Strength (psi)	240	221	231	460
Young's Modulus (psi)	11,317	10,291	11,161	NA

PROJECT MANAGEMENT

Immediately following the 2013 NCCC, a project manager, field manager, and four team captains were selected to manage various parts of the process to complete *Vanguard*: hull design and structural analysis, mix development and testing, construction, and aesthetics. Innovations and research were emphasized in the project scope and a schedule was set anticipating a new learning curve that was needed to evaluate each new idea while ensuring that milestone deadlines along the critical path were met.

The management team created a detailed schedule encompassing possible project innovations including the creation of a practice canoe, cement hydration research, and construction practices such as steam curing, pre-casting elements, a "coolant core", shotcrete, and a post-tensioning system (PTS). Research into these techniques had cut-off dates at which point it was determined whether or not to continue based on time, cost, and feasibility.

The project schedule developed a critical path based on major milestones of finishing the project, shown in Table 3. A margin of error was utilized for unexpected setbacks in the project to ensure these milestones of the process were completed on schedule. This included planning for innovation progress and the deadlines needed to complete milestones. *Vanguard* was designed and constructed by 23 team members accumulating a total of 6,100 man-hours shown in Figure 1.

Table 3. Project Major Milestones

Major Milestone	Variance	Reason
Practice Canoe Performance Evaluation	None	-
Mix Hydration Research	None	-
Final Hull Design	None	-
Mix Selection Finalized	None	-
Mold Completion	+ 7 days	Extra time over winter break
Placement Day	None	-

To ensure safety throughout the project, an experienced team member was selected to act as *Vanguard's* safety officer. After researching safety techniques, the safety officer met with team members to discuss safe construction and lab practices. Instructional meetings were held to discuss the proper handling and use of materials and Personal Protective Equipment (PPE) in accordance with the material safety data sheets (MSDS). The team's faculty advisor and multiple team members were OSHA certified. Additionally the team had a member of the UMass Lowell Environmental Health and Safety Office ensure these areas were safe work environments and stocked with the proper safety equipment.

Quality control measures were implemented throughout the entire process of the project. A quality control manager was appointed to supervise construction processes. All cementicious materials were hand-sieved to ensure high quality concrete mixes. Before placement days instructional sessions were held to ensure team members knew what their jobs entailed.

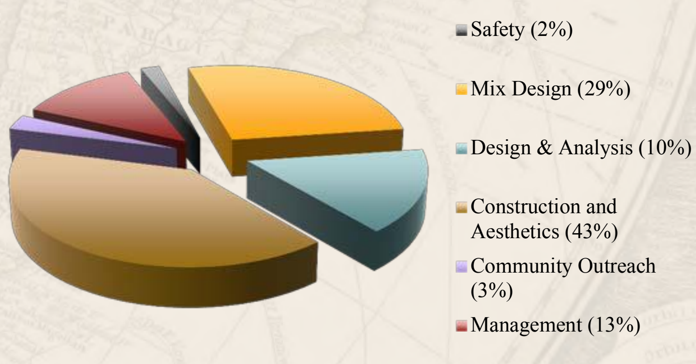


Figure 1. Man-hour Distribution Chart

Community outreach supplemented fundraising efforts. Through local news interviews, articles, and publicized school events, the team was able to recruit more members as well as find sponsors to make material and monetary donations. A crowdsource fundraising website (www.uml.edu/hawkhatchcanoe) was also implemented through the university to educate school alumni and the general public about what the UMass Lowell concrete canoe team is and how it benefits students. Funding could be donated directly through this site or sponsors could send a check to the school for the team.

The budget was set at $7,350 at the beginning of the year. $4,000 was allotted to aesthetics, construction, and mix design. Additional project expenses amounted to $1,880. The team saved $2,900 this year through fundraising efforts, material donations, and the use of recycled materials from the previous year; this reduced the final project costs by 20% of the anticipated cost. These savings will be carried over for next year's budget.

VANGUARD

Project Manager

Jonathan Ernst

Responsible for budgeting, fundraising, material procurement, and managing captains.

Quality Control Officer

Mark Procopio

Responsible for checking design and mix calculations, ensuring proper placement of concrete, and rule compliance.

Field Manager

Jonathan Nadeau

Responsible for scheduling, overseeing day-to-day operations, and setting critical path deadlines.

Safety Officer

Jeffrey Bruso

Responsible for working with Environmental Health and Safety, distributing MSDS, and scheduling saftey

Analysis Captain

Brendan Sprague

Responsible for hull design, classical two-dimentional structural analysis, and post tensioning system design.

Junior Captain: Michael Sprague

Team Members:
Julie Eaton, Jonathan Nadeau, Patrick Raistrick, Ryan Walker

Mix Design Captain

Patrick Raistrick

Responsible for cement hydration research, trial mix testing, and institution of an accelerated curing system.

Junior Captain: Maureen Kelly

Team Members:
Nicholas Brisbois, Jeffrey Bruso, Natalie Melkonian, Zachary Morris, Jonathan Nadeau, David Nader

Construction Captain

Zachary Greene

Responsible for construction of mold, canoe, stand, display, and sectional.

Junior Captain: Ryan Walker

Team Members:
Allan Bassett, Joseph Benoit, Nicholas Brisbois, Jeffrey Bruso, James McDermott, Jesse Merchant, Jonathan Nadeau, Mark Procopio, Patrick Raistrick, Sarah Shaw

Aesthetics Captain

Allan Bassett

Responsible for design of artwork, paper, presentation layout, and canoe graphics.

Junior Captain: Julie Eaton

Team Members:
Jeffrey Bruso, Maureen Kelly, Jonathan Nadeau, Mark Procopio, Patrick Raistrick, Ryan Walker

Paddling Coach

Joseph Benoit

Responsible for practice scheduling, conditioning of paddlers, and instructing proper paddling technique.

Team Members:
Zachary Greene, Maureen Kelly, Paige McNulty, Natalie Melkonian, Zachary Morris, Jonathan Nadeau, Cassandra Piorkowski, Patrick Raistrick, Timothy Roberts

HULL DESIGN AND STRUCTURAL ANALYSIS

The consensus from past paddlers was that previous hull designs did not adequately emphasize stability. This year's hull design and analysis team goal was to develop a stable hull than maintains the features required for speed. Instead of using a previous canoe hull as a baseline, the team decided to start from scratch. Using Prolines© 7, the team changed performance parameters to evaluate the effect on the canoe's stability, maneuverability, and speed.

The stability of a canoe is directly correlated to the shape of the bottom of the hull. A flat bottom gives the vessel a natural tendency to remain parallel to the water surface. To resist heeling when turning, secondary stability was achieved by slightly curving the base into flanged sidewalls (Randall 2010).

Maneuverability is essential in navigating the race course. For the canoe to turn efficiently the arch swing must be minimized at the bow and maximized at the stern. Increasing the stern rocker created this effect. Widening the stern portion of the hull and designing a V-notched bow allowed higher buoyancy and unimpeded water flow under the stern relative to the bow; this aided the turning mechanism. Figure 2 shows the cross section of the hull at the bow, stern, and mid-section.

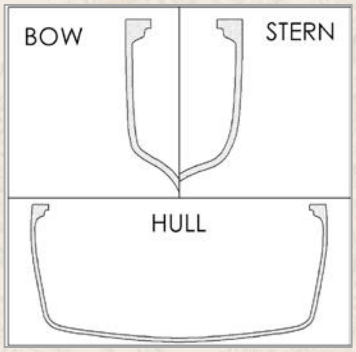


Figure 2. Hull Cross Section

Speed is optimized by decreasing frictional and wave-making resistance. During acceleration the canoe experiences the most resistance from frictional drag along the wetted area of the hull. Reducing the beam of the canoe decreases the wetted area and thus decreases the resistance. Increasing the length-to-beam ratio (L/B) achieves this, but decreases stability. The minimum L/B was set at 8.0 for sufficient stability. To minimize wave-making resistance, the bow must ride the crest and the stern must settle into the trough. The displacement-length ratio (DLR), shown in Equation 1, indicates how water is being displaced as the canoe cuts through it. Minimizing the DLR reduces wave-making resistance (Brewer 1993).

$$DLR = \frac{Displace\ weight\ (in\ tons)}{.01*((Water\ line\ length\ (in\ ft))^3} \qquad \text{(EQ. 1)}$$

The process of comparing these parameters against results in Prolines© 7 allowed the team to create a preliminary hull to be used for the practice canoe, *McPortland*. After the construction of *McPortland*, the paddling team was able to provide feedback on the performance of the hull. The hull design and analysis team incorporated this feedback and refined the final hull design for *Vanguard*, as seen in Table 4.

Table 4. Relationship Between Design Parameters and Hull Performance

Parameter	Effect on Performance	Final Hull Design for *Vanguard*
Bottom Shape of Hull	Stability	A hybrid bottom blending initial and secondary stability
Rocker	Maneuverability	Set the stern and bow rockers 4.5 in to 3.5 in respectively
Symmetry of Canoe	Maneuverability and Speed	Asymmetrical hull with the center of gravity 1.5 in towards the stern from the canoe center
Wetted Area	Speed	19.7 sq.ft empty to 39.0 sq.ft loaded with 4 paddlers
Length-to-Beam Ratio	Stability and Speed	Increased to 9.0 to accommodate speed without compromising stability
Displacement Length Ratio	Speed	Ranging from 24.1 (2-paddler loading) and 38.9 (4-paddler loading).

The hull design and analysis team modeled the canoe as a simply supported beam using two-dimensional analysis. To determine the maximum bending moment the paddlers were analyzed as point loads with assumed weights of 200 lb and 150 lb male and female paddlers, respectively. Archimedes' principle states that for an object submerged in water, the upward buoyant force is equal to the weight of the water displaced. The initial weight of the canoe was estimated to be 120 lb and distributed according to two-inch sectional volumes. The buoyant force was approximated into a triangular distributed load rather than a volume distributed load; this produced a more conservative bending moment (Beer 2012).

The hull was analyzed assuming unreinforced concrete for six primary load cases: two-paddler male, two-paddler female, four-paddler co-ed, two-person carry, punching shear, and hydrostatic transverse. Using Solidworks®, the team extracted the cross-sectional properties of the canoe including the area, moment of inertia, and centroid. The canoe is fully supported during transportation so this load case was considered negligible. The analysis team determined the stresses and moments acting upon the canoe in one-inch intervals using Microsoft® Excel.

Structural elements were added to reduce both compressive and tensile stresses on the canoe. Gunwales reduced tensile stresses acting along the top of the canoe. Three ribs provided rigidity, torsional resistance, and helped prevent sidewall buckling from compression stresses.

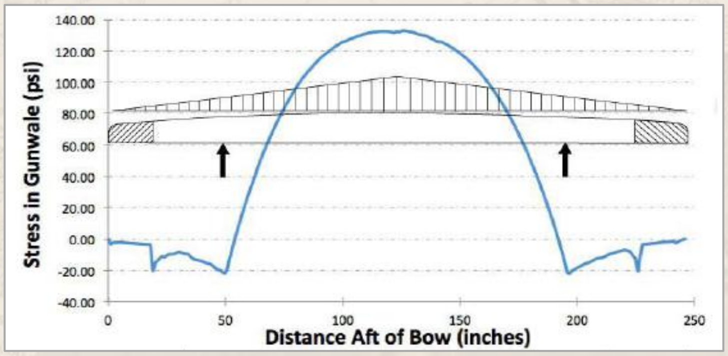


Figure 3. Stress Distribution for Two-paddler Male Sprint

After evaluating the six load cases, the team discovered that the two-paddler male loading created the largest moment on the canoe and largest maximum tensile stresses. The distribution of stresses for two paddler male loading is shown in Figure 3. The primary structural zone for the canoe was identified as the location of these stresses—along the bottom of the gunwales.

In September the structural analysis team decided to start research for a post-tensioning system (PTS). In the past UMass Lowell has relied upon structural elements and mesh reinforcement to alleviate stresses on the canoe. A PTS would further reduce the tensile stresses in the gunwales of the canoe. Using "safe working load" industry standards, the team selected 20% of the ultimate tensile strength of the 7x7 galvanized aircraft cable, which resulted in a 43.6 lb tension force for the system (USBR 2009).

Implementing the PTS required additional analysis of the canoe and gunwale design. The team analyzed block shear resistance of one-inch gunwale cross-sections to evaluate the risk of cable break-out. Tensile rupture capacity and shear strength were considered, and the break-out potential of the gunwales for a range of failure envelopes was calculated (ACI 318-11). The centripetal force caused by the curved cable never exceeded the 58 lb worst-case scenario determined from this iterative process. The total stress after the PTS is determined using Equation 2, where M is the moment, $\bar{y}$ is the distance to the centroid, I is the moment of inertia, A_c is the area of concrete, e is the eccentricity, and r is the cross sectional radius of gyration (Nawy 1989).

$$\sigma = \frac{M\bar{y}}{I} - \frac{P_t}{A_c}\left(1 - e\frac{\bar{y}}{r^2}\right) \quad \text{(EQ. 2)}$$

The PTS resulted in only a 4 psi decrease in gunwale stresses at the center of the hull, but the research performed this season will provide a basis for further study in future seasons.

The cable anchors were designed to be braced against bearing plates in the bulkhead of the canoe. An analysis of the 40 lb force over the cross sectional area of each gunwale at the bulkheads was performed to determine stresses created in the bulkheads. In addition to the analysis of the PTS stresses, the team determined that the carrying load case was a critical load case for the bulkhead. Once mix strengths were known, the team was able to maximize the amount of foam in the bulkhead after considering the total stress.

The team also analyzed the stresses in the hull and determined that punching shear was the critical load case. A combination of carbon fiber and fiberglass mesh reinforcement provided adequate reduction in punching shear stresses. By analyzing the canoe as multiple zones of influence with different strength requirements, the mix design team could design multiple mixes for the canoe. A dynamic amplification loading factor of 1.25 was applied to each stress value. This accounted for variables beyond the scope of static analysis, such as stress increases from paddle strokes, force impulses, and light heeling (Paradis 2007). The requirements and critical load cases are outlined in Table 5.

Table 5. *Vanguard* Tensile Strength Requirements

Stress Zone	Required Strength	Critical Load Case
Structural	135 psi	Two-Paddler Male Sprint
Bulkhead	34 psi	PTS Plate Bearing and Two-Person Carry
Hull	67 psi	Punching Shear

DEVELOPMENT AND TESTING

At the start of the concrete development process, two facts became apparent to *Vanguard's* mix design team. First, concrete derives its strength from the bonding of the cementitious paste to the aggregate material. Second, the chemistry of hydration for Portland cement—which is responsible for the cementitious paste's bond strength—remains the same regardless of the aggregate used.

Knowing this the mix design team set three goals for the course of the year: (1) maximize the bond strength of the concrete with respect to both aggregate and reinforcement, (2) develop three separate mixes for use in *Vanguard* based upon the requirements for the three major zones: hull, bulkheads, and structural elements, and (3) institute an accelerated curing system for expedited preliminary testing.

Since bond strength is directly related to the hydration of Portland cement, *Vanguard's* concrete mixtures were developed by knowing how much calcium-silicate-hydrate (C-S-H) gel—the source of concrete's bond strength—and hydrated lime (CH) are created during the hydration reactions of dicalcium silicate (C_2S) and tricalcium silicate (C_3S). This can be seen in Equations 3 and 4 respectively.

$$2C_2S + 7H_2O \rightarrow C - S - H + CH \quad \text{(EQ. 3)}$$

$$2\mathrm{C_3S} + 7\mathrm{H_2O} \rightarrow \mathrm{C - S - H + 3CH} \quad \text{(EQ. 4)}$$

A tensile stress of 135 psi occurring just beneath the gunwale was considered to be the governing structural element stress based upon *Vanguard's* structural analysis. After applying a Factor of Safety (FOS) of 1.3, it was determined that the required tensile strength for *Vanguard's* structural element mix would have to surpass 176 psi. As such, *Moswetuset's* mix (44.6 pcf, 386 psi tensile strength, w/c 0.7) with a 4:1 Type I White Portland cement/metakaolin content was used as a baseline for determining an appropriate cement matrix.

Taking into consideration the molar weights and percentage by volume of each constituent material involved in the hydration process, the mix team determined that *Moswetuset* had a hydrated lime content of 2.3 % by weight—approximately 3 lb. Since hydrated lime is hydrophilic and serves only to weaken concrete over time due to its high permeability, the mix team limited its content even further by relying on the pozzolanic reaction shown in Equation 5:

$$\mathrm{Pozzolan + CH \rightarrow C - S - H} \quad \text{(EQ. 5)}$$

Using this reaction in conjunction with pozzolans such as white silica fume and high reactivity metakaolin, *Vanguard's* mix team was able to decrease the hydrated lime content to 0.00304 % by weight or 0.36 lb using Type I White Portland cement, high reactivity metakaolin, and white silica fume at volumetric quantities of 76.35%, 17.22%, and 6.43% respectively.

In addition to facilitating the pozzolanic reaction, high reactivity metakaolin was chosen for its ability to deter the long-term alkali-silica reaction (ASR) which causes expansive pressures inside aggregate material in concrete, leading to an initial loss of strength and eventual rupture failure (Cement and Concrete Research 2000). A breakdown of various pozzolans and their potential benefits can be seen in Table 6.

With the goal of utilizing multiple mix designs this year, the cement matrix outlined above was held constant in order to ensure deformational compatibility between designs with the exception of the aesthetic pre-cast elements (Johnston and Beer 2006).

Table 6. Pozzolan Properties and Benefits

Pozzolan	Molar Weight	Potential Benefits
White Silica Fume	60 g/mol	Low molar weight, consumes lime with less material, high aesthetic quality
Fly Ash	77 g/mol	Low molar weight, increases durability and workability
Metakaolin	223 g/mol	Deters ASR, high aesthetic quality, good for "fine tuning"
Pumice Powder	72 g/mol	Low molar weight, acts as natural shrinkage reducer

Using previous research performed for *Revolution* and *Moswetuset* on the topic of aggregate gradation in concrete, *Vanguard's* mix design team chose to utilize only fine aggregates in order to maximize the bonding surface area of all mixes used for testing. 3M™'s K15 and 3M™'s S38HS were selected due to their low specific gravities and respective average particle sizes of 60 μm and 42 μm. Testing showed that a 3:2 ratio of K15 to S38HS proved sufficient for particle gradation. Holding this gradation constant for all designs ensured stresses throughout the entire canoe were decreased within the interfacial transition zone—concrete's tensile failure zone—by allowing more aggregate material to be coated by the cementitious paste (Kosmatka 2002).

Concrete reinforcement consisted of a fiberglass mesh, carbon fiber mesh, and a matrix of 1/4 in polyvinyl alcohol (PVA) fibers added directly to the mix itself. The combination of PVA—at quantities ranging from 1.75% to 3%—and mesh reinforcement throughout the entire hull and gunwales helped to alleviate internal stresses and increase the overall flexural strength of the concrete.

Furthermore, Eclipse® Floor 200 Shrinkage Reducer and ADVA® Cast 575 Super Plasticizer were used at manufacturer's recommended dosage rates to decrease shrinkage and achieve desired workability. Silpro® C-21 Liquid Latex with a solids content of 20% was used as the only source for hydration. This dosage of latex created an air entrainment of approximately 20% by volume, which proved sufficient in minimizing unit weight without causing "pocketing" of the concrete.

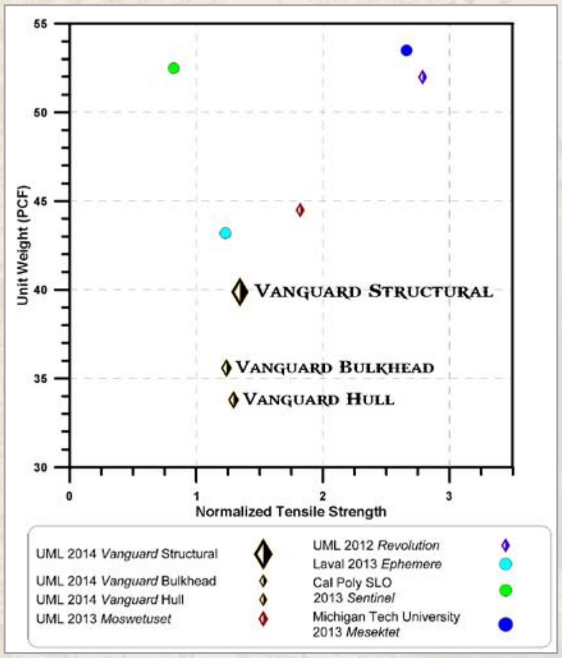


Figure 4. Concrete Normalization Chart

Vanguard's mix team then employed an iterative design process by varying the percentage of cementitious paste (CP %), w/c ratio, and PVA fiber content while relying upon normalization for direct comparison (Figure 4) until the three mixes initially sought after were designed. Tensile strengths for all mixes were normalized using Equation 6:

$$Normalized\ Strength = \frac{Ultimate\ Strength}{Required\ Strength} \qquad \text{(EQ. 6)}$$

McPortland's cement matrix of Type I White Portland cement, metakaolin, and silica fume was used for *Vanguard*'s pre-cast elements. Although these elements were purely aesthetic, K15 and CenoStar's cenospheres left over from *Revolution*, mixed at a 4:1 ratio and a CP % of 45% ensured they would have enough strength to withstand accidents during construction.

In order to minimize the amount of time required for testing this year, *Vanguard's* mix design team implemented a standard steam curing cycle (Mindess and Young 1981) using a steam bath donated by UMass Lowell's Hazardous Waste Treatment Laboratory (Figure 5). This allowed for the mix team to test samples with 28-day maturity after just 18 hours of curing. Due to the rather small size of the steam bath and to save on material costs, 2 in x 4 in cylinders were used instead of 3 in x 6 in cylinders for initial testing in accordance with ASTM C496 split cylinder tests for tensile strength. This allowed the mix design team to decrease UMass Lowell's environmental impact greatly, with the smaller cylinders requiring about 1/5 of the mix materials necessary for testing. MSDS were reviewed for each material; areas were sealed off and well ventilated, and the appropriate PPE was worn throughout mix development.

Steam curing of concrete was found to have adverse effects on both unit weight and strength when done properly. Densification of concrete occurs due to swelling of the cementitious paste, leading to a loss of air entrainment and crushing of the glass microsphere aggregate. As such only the aesthetic precast elements were steam cured for the final product. Steam cured test samples were used only for relative comparison and finalists were re-evaluated in accordance with ASTM C496 and ASTM C39 for compressive strength. 3 in x 6 in cylinders and 2 in x 2 in square compression cubes cast on placement day determined *Vanguard*'s true properties and can be shown in Table 7.

Figure 5. Steam Cured Elements

Table 7. Actual Concrete Properties

MIX ID	Unit Weight	w/c	Requirement	Requirement Fulfilled by	Tensile Strength
Structural Elements	41.1 pcf	0.6	178 psi (Tensile)	Increased CP %	240 psi
Hull/Patch	33.8 pcf	0.7	High Workability	Increased Super Plasticizer Content	221 psi
Bulkheads	35.6 pcf	0.7	Low Slump	Increased Fiber Content	231 psi
Pre-cast	52.2 pcf	0.7	Consolidating	Increased CP % and w/c	460 psi

CONSTRUCTION

Vanguard's construction team began theorizing and refining construction methods in early September. A male mold was chosen to accurately place structural elements and inlays, make the sanding process more convenient, and for the overall ease of construction. Before starting the mold, it was important to level the existing table on which the canoe would be constructed. The top of the table would act as the bottom of the mold therefore any warping would be reflected in the final product. After reinforcing and sealing the table with polyurethane, the mold was ready for construction.

Beginning with a Solidworks® model, 100 paper cross-sections were plotted at two-inch intervals. They were then transferred onto two-inch thick polystyrene foam sheets—chosen for its ability to be easily repurposed in other applications. This allowed the exact transfer of *Vanguard*'s shape. After cutting these templates with a band saw, *Vanguard*'s mold was glued together and sanded with 110-grit sandpaper. Gunwales were cut into the mold using a track system in conjunction with a foam-cutting hot knife. This provided a seamless gunwale spanning from bow to stern. Three semi-circular ribs (d = 0.5 in) were carefully routed into specified sections to achieve a smooth, precise shape. Additionally, a series of aesthetic rivets were imprinted into the mold using a router, and hot glue was applied along the mold's sidewalls to give off the appearance of brickwork behind a network of trusses. The brickwork inlays and rivet outlays along with steam pipe style ribs provided *Vanguard* with a truly industrialized steampunk feel.

Inspired by the mix development research, the construction team created a "coolant core" to decrease the man-hours needed to keep *Vanguard* moist for 28 days. The "coolant core" was developed through the application of heat transfer theories. (Moran et. al. 2011). As shown in Figure 6, a series of 3/8 in wide channels were routed into the top and sides of the mold, lined with vinyl tubing, and connected to a pump system that would keep an antifreeze/water solution flowing throughout the entire mold. By locating the reservoir outside, the "coolant core" was able to take advantage of New England's cold winters to self-cool the solution. This kept the surface of the mold a consistent 5º F cooler than the ambient temperature—thereby constantly attracting water vapor to the concrete. This reduced microsphere aggregate expansion, heat shrinkage cracking, and air entrainment loss for the duration of the 28-day curing cycle. The "coolant core" also allowed for less mold expansion and prevented stress cracks along the canoe. The channels of the "coolant core" and other slight imperfections were smoothed over with drywall compound to give *Vanguard*'s inner hull a perfect shape before inlays were added to the mold.

Figure 6. Routing of Channels

By getting an early start in September, the construction team was able to place *Vanguard* a full month earlier than last year. Placement day was completed utilizing six teams, each of which was led by an experienced team member. These teams were responsible for (1) concrete mix, (2) first layer/second layer hull placement, (3) bulkhead placement, (4) structural element and PTS placement, (5) reinforcement placement, and (6) safety/quality control. To guarantee superior quality, all six teams attended instructional classes led by the construction captain to illustrate the proper placement techniques of the PTS and the three different mixes developed for *Vanguard*.

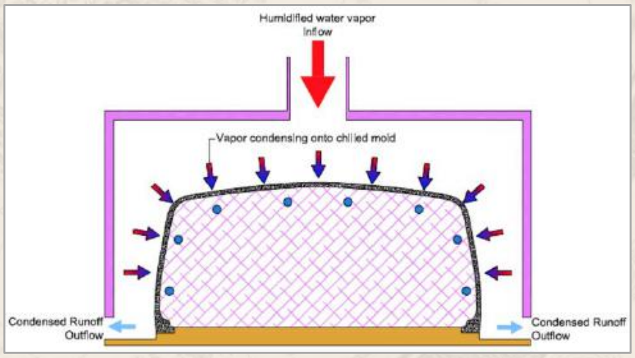


Figure 7: Hydration Chamber/"Coolant Core"

Prior to placement day, the hydration tent used in previous years was constructed to provide a moist environment to keep the concrete workable for the entire placement. Additionally, a two-inch thick foam hydration chamber was constructed. The chamber had three ducts attached to humidifiers set to 90% humidity that pumped water vapor into an enclosed volume 93.44% smaller than a hydration tent. Used in conjunction with the "coolant core" as shown in Figure 7, this chamber allowed for more condensation directly onto the concrete, thereby making *Vanguard*'s curing environment truly optimized and reducing excess water use.

Vanguard was hand-placed from stern to bow starting with a 3/16 in first layer as shown in Figure 8. Wooden depth checkers were used to maintain a constant thickness throughout the canoe. In between first and second layers, fiberglass mesh was placed along the length of the hull with a 4 in overlap for each piece. Carbon fiber mesh was then placed in addition to the fiberglass mesh below paddlers' knees and along the middle rib for increased resistance to punching shear and flexure in these zones.

Gunwales and ribs received carbon fiber strip inserts as well, making *Vanguard* "fully reinforced". Finally, a second 1/4 in layer of concrete was placed in a similar manner as the first which brought the hull thickness to 7/16 in. This provided a buffer to account for surface irregularities that would be sanded down to the average thickness of 3/8 in.

Figure 8. Concrete and Reinforcement Placement

Galvanized aircraft steel tendons (d = 3/64 in) for the PTS were anchored in the bulkhead at the bow and stern using steel bearing plates and copper crimps. Surrounded by plastic sheathing, the tendons were cast in place using a track system along the gunwale that ensured a smooth arc spanning the length of the canoe. An open space just after the bow bearing plate allowed access to tension the steel cable after the curing process. After 28 days these tendons were crimped and tensioned to the pre-determined specification of 43.6 lb at the bow using the "turn of the nut" approach (Nawy 1989).

After allowing concrete to set for 24 hours, the canoe was then covered with the hydration chamber that was set to 90% humidity. This environment was held constant until the 14^{th} day of curing when the hydration chamber was removed and wet sanding began on the outer hull. *Vanguard* was kept in the larger hydration tent under controlled humidity until it had cured for 28 days.

Starting with 60-grit sandpaper, *Vanguard*'s construction team was able to wet sand the outer hull up to 500-grit by day 28. With the use of wooden gauges modified from *Moswetuset* and shadow sanding techniques, imperfections on the outer hull were found and sanded. At this point the canoe was ready to be de-molded.

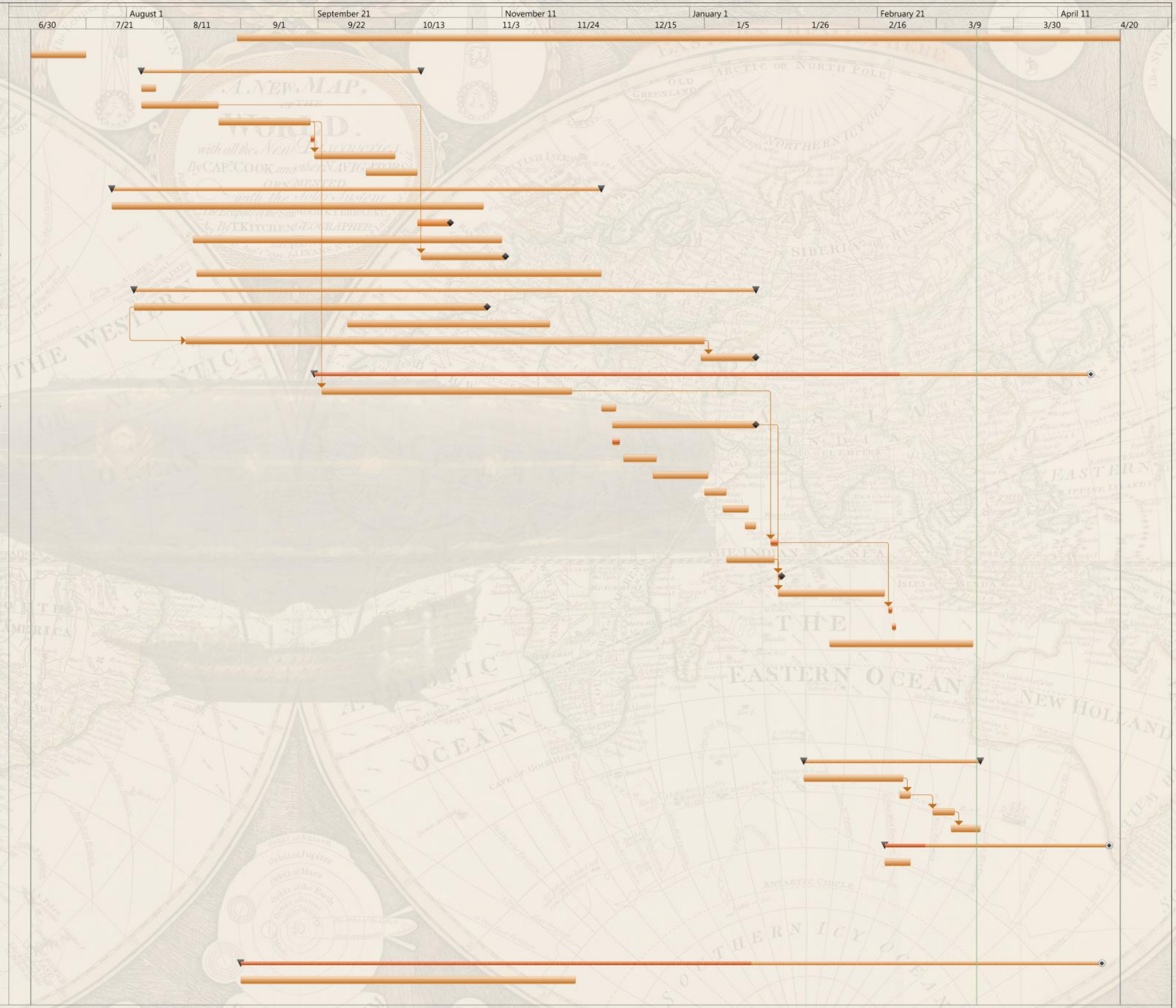
After flushing out the vinyl tubing in the mold, the canoe was flipped onto stands and the mold was carefully removed one section at a time. The process consisted of cutting out four sections in the center with a foam-cutting hot knife. The remaining smaller sections were pulled towards the center of the canoe and lifted out with ease. This process was quick and did not subject the canoe to unnecessary stresses. Some sections were reused as part of the sectional, and the rest will be recycled for construction in the 2015 season.

Excess drywall compound on the inner hull was removed and light patching was performed. Sanding advanced up to 800-grit on the inside and 1500-grit on the outside of the canoe. After sanding the aesthetics team will take their blank canvas and transform it into *Vanguard*. Aesthetic pre-cast elements will be placed onto the bulkheads and graphics will be applied using custom stencils and freehand pencil outlines followed by the application of two layers of water-based stain to give *Vanguard* rich colors. Vinyl lettering is to be adhered at the bow and stern along with two layers of sealer that will be sanded up to 2500-grit sandpaper, revealing a smooth finish.

Many precautions were taken to ensure a safe work environment throughout the process. Workspaces were kept clean and clear of all hazards and MSDS were displayed and reviewed before the use of any hazardous product. Rooms were properly ventilated and PPE was worn at all times. An overseeing field manager, safety manager, and quality control manager monitored each process—ensuring protocols were followed. This supervision created a better final product and above all else, a safer experience for all members.

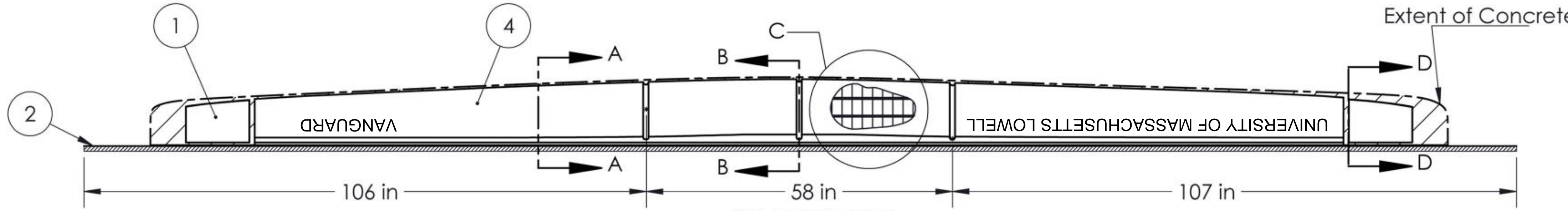
VANGUARD

ID	Task Name	Baseline Start	Baseline Finish	Expected and Actual Duration	Actual Start	Actual Finish
1	Fundraising	Sat 8/31/13	Sun 4/27/14	240 days	Sat 8/31/13	Sun 4/27/14
2	Planning Meetings	Sat 7/6/13	Sat 7/20/13	14 days	Sat 7/6/13	Sat 7/20/13
3	**Practice Canoe (McPortland)**	**Mon 8/5/13**	**Sat 10/19/13**	**76 days**	**Mon 8/5/13**	**Sat 10/19/13**
4	Lab Organization	Mon 8/5/13	Fri 8/9/13	4 days	Mon 8/5/13	Thu 8/8/13
5	Preliminary Hull Design	Mon 8/5/13	Sat 8/24/13	21 days	Mon 8/5/13	Sun 8/25/13
6	Mold Construction	Sun 8/25/13	Thu 9/19/13	24 days	Mon 8/26/13	Thu 9/19/13
7	Canoe Placement	Fri 9/20/13	Fri 9/20/13	1 day	Fri 9/20/13	Fri 9/20/13
8	Canoe Cure	Sat 9/21/13	Sat 10/12/13	21 days	Sat 9/21/13	Sat 10/12/13
9	Sanding/Sealing	Sat 10/5/13	Wed 10/16/13	18 days	Sat 10/5/13	Fri 10/18/13
10	**Hull Design and Structural Analysis**	**Sun 7/28/13**	**Sat 12/7/13**	**132 days**	**Sun 7/28/13**	**Sat 12/7/13**
11	Hull Design Research	Sun 7/28/13	Sat 11/2/13	100 days	Sun 7/28/13	Tue 11/5/13
12	Practice Canoe Evaluation	Sat 10/19/13	Sat 10/26/13	9 days	Sat 10/19/13	Sun 10/27/13
13	Canoe Modeling	Sun 8/18/13	Sat 11/9/13	84 days	Mon 8/19/13	Sun 11/10/13
14	Final Hull Design	Sat 10/26/13	Sat 11/9/13	23 days	Sun 10/20/13	Mon 11/11/13
15	Structural Analysis	Sun 8/18/13	Sat 12/7/13	110 days	Tue 8/20/13	Sat 12/7/13
16	**Mix Development and Testing**	**Sat 8/3/13**	**Sat 1/18/14**	**169 days**	**Sat 8/3/13**	**Sat 1/18/14**
17	Hydration Research	Sat 8/3/13	Sat 11/9/13	96 days	Sat 8/3/13	Wed 11/6/13
18	Material Procurement	Sat 9/28/13	Sat 11/23/13	55 days	Mon 9/30/13	Sat 11/23/13
19	Testing	Sat 8/17/13	Sun 12/29/13	141 days	Sat 8/17/13	Sat 1/4/14
20	Final Mix Selection	Sat 1/4/14	Sat 1/11/14	15 days	Sat 1/4/14	Sat 1/18/14
21	**Construction**	**Sat 9/21/13**	**Sat 4/19/14**	**211 days**	**Sat 9/21/13**	**NA**
22	Construction Techniques Research	Sat 9/21/13	Fri 11/29/13	68 days	Mon 9/23/13	Fri 11/29/13
23	Lab Organization	Sun 12/8/13	Sat 12/14/13	4 days	Sun 12/8/13	Wed 12/11/13
24	Mold Construction	Wed 12/11/13	Fri 1/24/14	39 days	Wed 12/11/13	Sat 1/18/14
25	- Cross Sections Printed	Wed 12/11/13	Fri 12/13/13	2 days	Wed 12/11/13	Thu 12/12/13
26	- Section Cutting	Sat 12/14/13	Sat 12/21/13	9 days	Sat 12/14/13	Sun 12/22/13
27	- Mold Sanding	Sat 12/21/13	Sat 1/4/14	15 days	Sun 12/22/13	Sun 1/5/14
28	- Features and Inlays Added	Sat 1/4/14	Fri 1/10/14	6 days	Sun 1/5/14	Fri 1/10/14
29	- Installation of coolant tubes	Fri 1/10/14	Fri 1/17/14	7 days	Fri 1/10/14	Thu 1/16/14
30	- Mold Mudded	Fri 1/17/14	Fri 1/24/14	3 days	Thu 1/16/14	Sat 1/18/14
31	Post Tension Installment	Thu 1/23/14	Fri 1/24/14	2 days	Thu 1/23/14	Fri 1/24/14
32	Hydration Chamber construction	Sat 1/11/14	Fri 1/24/14	14 days	Sat 1/11/14	Thu 1/23/14
33	Canoe Placement	Sat 1/25/14	Sat 1/25/14	1 day	Sat 1/25/14	Sat 1/25/14
34	Wet Curing	Sat 1/25/14	Sat 2/22/14	29 days	Sat 1/25/14	Sat 2/22/14
35	Mold Removal	Sat 2/22/14	Sat 2/22/14	1 day	Mon 2/24/14	Mon 2/24/14
36	Tensioning of Cables for PTS	Sun 2/23/14	Sun 2/23/14	1 day	Tue 2/25/14	Tue 2/25/14
37	Stripping/Sanding/Patching	Sat 2/8/14	Tue 3/18/14	39 days	Sat 2/8/14	Tue 3/18/14
38	Staining	Sat 3/22/14	Fri 4/18/14	28 days	NA	NA
39	Sealing	Sat 4/19/14	Thu 4/24/14	6 days	NA	NA
40	Completed Canoe	Thu 4/24/14	Thu 4/24/14	1 day	NA	NA
41	Display Construction	Tue 3/4/14	Tue 4/8/14	36 days	Tue 3/4/14	NA
42	Canoe Stand Construction	Thu 3/13/14	Sat 4/12/14	31 days	Thu 3/13/14	NA
43	Sectional Construction	Mon 3/3/14	Wed 4/16/14	45 days	Mon 3/3/14	NA
44	**Design Paper**	**Thu 2/13/14**	**Fri 3/21/14**	**48 days**	**Sat 2/1/14**	**Thu 3/20/14**
45	Working Draft	Thu 2/13/14	Thu 2/27/14	27 days	Sat 2/1/14	Thu 2/27/14
46	Peer Revisions	Thu 2/27/14	Sat 3/1/14	3 days	Thu 2/27/14	Sat 3/1/14
47	Group Review	Sun 3/2/14	Fri 3/7/14	6 days	Sat 3/8/14	Thu 3/13/14
48	Final Draft	Sat 3/8/14	Fri 3/21/14	7 days	Thu 3/13/14	Thu 3/20/14
49	**Presentation**	**Sun 2/23/14**	**Thu 4/24/14**	**61 days**	**Sun 2/23/14**	**NA**
50	Presenter Selection	Sun 2/23/14	Sat 3/1/14	7 days	Sun 2/23/14	Sat 3/1/14
51	Script Development	Sun 3/16/14	Sat 3/29/14	14 days	Sun 3/16/14	NA
52	Presenation Design	Sun 3/16/14	Wed 4/16/14	32 days	Sun 3/16/14	NA
53	Rough Presentation	Sun 3/30/14	Sat 4/5/14	7 days	NA	NA
54	Peer Critiques	Sat 4/5/14	Sun 4/6/14	2 days	NA	NA
55	Final Presenation	Mon 4/7/14	Thu 4/24/14	18 days	NA	NA
56	**Paddling**	**Sun 9/1/13**	**Tue 4/22/14**	**234 days**	**Sun 9/1/13**	**NA**
57	Fall Practice/Tryouts	Sun 9/1/13	Sat 11/30/13	91 days	Sun 9/1/13	Sat 11/30/13
58	Spring Practice	Sun 3/16/14	Tue 4/22/14	38 days	Sun 3/16/14	NA

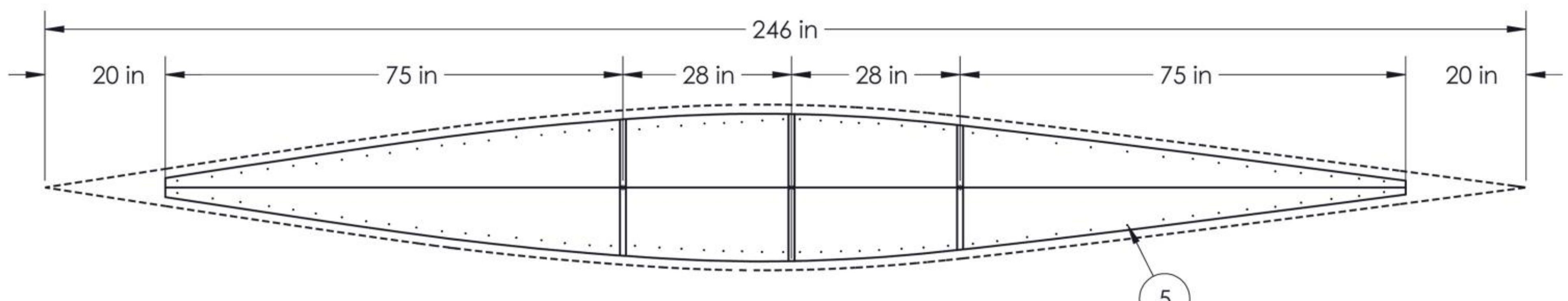


Project: VANGUARD
Date: Thu 3/20/14

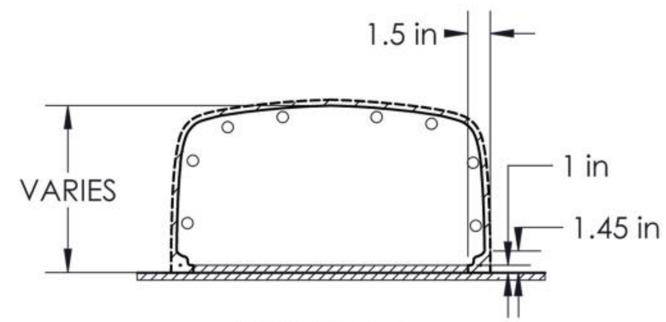
Task — Progress — Milestone — Start — Finish



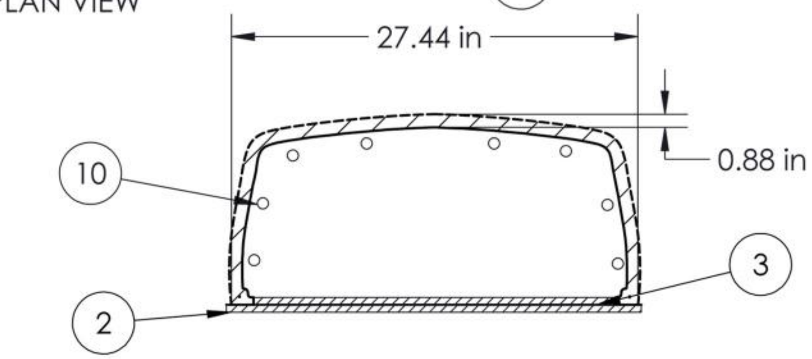
ELEVATION VIEW



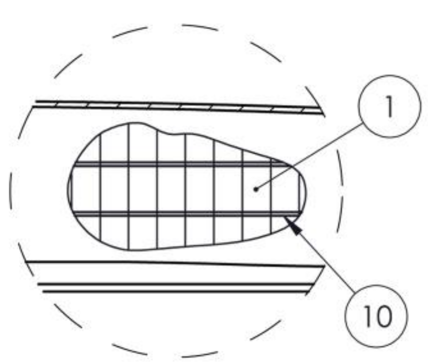
PLAN VIEW



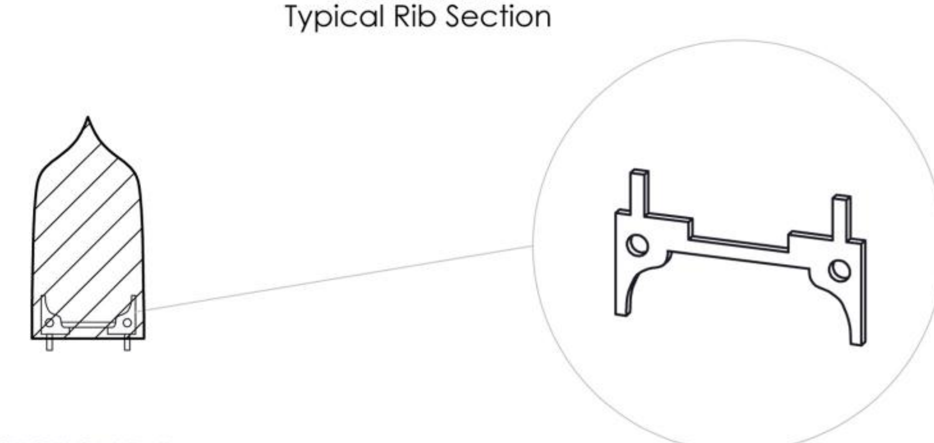
SECTION A-A
Typical Hull Section



SECTION B-B
Typical Rib Section



DETAIL C
XPS Detail



SECTION D-D
Tension Plate Cut Out

University of Massachusetts Lowell

Bill of Materials

No.	Qty.	Description
1	6 Pieces	4' x 8' x2" XPS Foam
2	3 Sheets	1/2" Plywood
3	3 Sheets	5/8" Plywood
4	3/4 gal.	Drywall Compound
5	1 lbs.	4" Deck Screws
6	1 lbs.	2" Deck Screws
7	6 Cans	Polystyrene Adhesive
8	1/4 gal.	Release Agent
9	20 Sticks	Hot Glue
10	100 Ft.	3/8" Vinyl Tubing
11	2	1/4" Brass Barb Splice
12	4	#4 Pipe Clamp
13	2 qt.	Water-based Polyurethane

Vanguard
Mold Design Drawing

General Notes:

1. Drawings not to Scale
2. Construction Adhesive appplied to one side of each foam piece
3. Some screws omitted for clarity
4. Plywood base is two sheets thick
5. Plywood to extend 2" beyond final concrete surface

ENGINEER	Brendan Sprague	CHECKED	Jonathan Nadeau
DRAWN	Michael Sprague	DATE	3/15/2014
			Sheet 10

APPENDIX A—REFERENCES

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APPENDIX B—MIXTURE PROPORTIONS

	Mixture ID: Structural Elements		Design Proportions (Non SSD)		Actual Batched Proportions		Yielded Proportions	
Y_D	Design Batch Size (ft³):	0.173						
	Cementitious Materials	SG	Amount (lb/yd³)	Volume (ft³)	Amount (lb)	Volume (ft³)	Amount (lb/yd³)	Volume (ft³)
CM1	White Portland Cement	3.15	484.01	2.462	3.10	0.016	435.51	2.216
CM2	White Silica Fume	2.20	28.49	0.208	0.18	0.001	25.63	0.187
CM3	Metakaolin	2.60	90.10	0.555	0.58	0.004	81.08	0.500
	Total Cementitious Materials:		602.61	3.23	3.86	0.021	542.22	2.90
	Fibers							
F1	PVA	1.30	31.99	0.394	0.20	0.003	28.78	0.355
	Total Fibers:		31.99	0.39	0.20	0.003	28.78	0.35
	Aggregates							
A1	3M™ K15 Abs: 0 %	0.15	69.76	7.453	0.45	0.048	62.77	6.706
A2	3M™ S38HS Abs: 0 %	0.38	117.82	4.969	0.75	0.032	106.02	4.471
	Total Aggregates:		187.59	12.42	1.20	0.080	168.79	11.18
	Water							
W1	Water for CM Hydration (W1a + W1b)	1.00	426.09	6.828	2.73	0.044	383.39	6.144
	W1a. Water from Admixtures		426.09		2.73		383.39	
	W1b. Additional Water		0.00		0.00		0.00	
W2	Water for Aggregates, SSD	1.00	0.00		0.00		0.00	
	Total Water *(W1 + W2)* **:**		426.09	6.83	2.73	0.044	383.39	6.14
	Solids Content of Latex Admixtures and Dyes							
S1	Latex (if used)	1.10	81.15	1.182	0.13	0.002	73.02	1.064
	Total Solids of Admixtures:		81.15	1.18	0.13	0.002	73.02	1.06
	Admixtures (including Pigments in Liquid Form)	% Solids	Dosage (fl oz/cwt)	Water in Admixture (lb/yd³)	Amount (fl oz)	Water in Admixture (lb)	Dosage (fl oz/cwt)	Water in Admixture (lb/yd³)
Ad1	Silpro C-21 Latex *9.2 lb/gal*	20%	938.89	404.95	9.39	2.59	844.8	364.38
Ad2	ADVA Cast 575® *8.9 lb/gal*	40%	19.58	8.17	0.20	0.05	17.6	7.35
Ad3	Eclipse® Floor 200 *7.9 lb/gal*	1%	34.85	12.96	0.35	0.08	31.4	11.66
	Water from Admixtures *(W1a)* **:**			426.09		2.73		383.39
	Cement-Cementitious Materials Ratio		0.803		0.803		0.803	
	Water-Cementitious Materials Ratio		0.60		0.60		0.60	
	Slump, Slump Flow, *in*.		2.00		2.00		2.00	
M	Mass of Concrete. *lbs*		1329.42		8.13		1196.21	
V	Absolute Volume of Concrete, *ft³*		24.05		0.15		21.64	
T	Theorectical Density, *lb/ft³ = (M / V)*		55.27		54.77		55.27	
D	Design Density, *lb/ft³ = (M / 27)*		49.24					
D	Measured Density, *lb/ft³*				42.300		42.300	
A	Air Content, *% = [(T - D) / T x 100%]*		10.92		22.76		23.47	
Y	Yield, *ft³ = (M / D)*		**27**		0.1923		**27**	
Ry	Relative Yield *= (Y / Y_D)*				1.111			

	Mixture ID: Bulkhead		Design Proportions (Non SSD)		Actual Batched Proportions		Yielded Proportions	
Y_D	Design Batch Size (ft^3):	0.173						
	Cementitious Materials	SG	Amount (lb/yd^3)	Volume (ft^3)	Amount (lb)	Volume (ft^3)	Amount (lb/yd^3)	Volume (ft^3)
CM1	White Portland Cement	3.15	385.50	1.961	2.47	0.013	337.53	1.717
CM2	White Silica Fume	2.20	22.67	0.165	0.15	0.001	19.85	0.145
CM3	Metakaolin	2.60	71.76	0.442	0.46	0.003	62.83	0.387
	Total Cementitious Materials:		479.93	2.57	3.08	0.016	420.20	2.25
	Fibers							
F1	PVA	1.30	48.99	0.604	0.31	0.004	42.89	0.529
	Total Fibers:		48.99	0.60	0.31	0.004	42.89	0.53
	Aggregates							
A1	3M™ K15 Abs: 0 %	0.15	75.75	8.093	0.49	0.052	66.32	7.086
A2	3M™ S38HS Abs: 0 %	0.38	127.94	5.396	0.82	0.035	112.02	4.724
	Total Aggregates:		203.69	13.49	1.31	0.086	178.34	11.81
	Water							
W1	Water for CM Hydration (W1a + W1b)	1.00	393.33	6.303	2.52	0.040	344.38	5.519
	W1a. Water from Admixtures		393.33		2.52		344.38	
	W1b. Additional Water		0.00		0.00		0.00	
W2	Water for Aggregates, SSD	1.00	0.00		0.00		0.00	
	Total Water *(W1 + W2)* **:**		393.33	6.30	2.52	0.040	344.38	5.52
	Solids Content of Latex Admixtures and Dyes							
S1	Latex (if used)	1.10	74.76	1.089	0.16	0.002	65.45	0.954
	Total Solids of Admixtures:		74.76	1.09	0.16	0.002	65.45	0.95
	Admixtures (including Pigments in Liquid Form)	% Solids	Dosage (fl oz/cwt)	Water in Admixture (lb/yd^3)	Amount (fl oz)	Water in Admixture (lb)	Dosage (fl oz/cwt)	Water in Admixture (lb/yd^3)
Ad1	Silpro C-21 Latex *9.2 lb/gal*	20%	1085.98	373.04	10.86	2.39	950.8	326.62
Ad2	ADVA Cast 575® *8.9 lb/gal*	40%	22.00	7.31	0.22	0.05	19.3	6.40
Ad3	Eclipse® Floor 200 *7.9 lb/gal*	1%	43.80	12.97	0.44	0.08	38.3	11.36
	Water from Admixtures *(W1a)* **:**			393.33		2.52		344.38
	Cement-Cementitious Materials Ratio		0.803		0.803		0.803	
	Water-Cementitious Materials Ratio		0.70		0.70		0.70	
	Slump, Slump Flow, *in*.		≈ 0.00		≈ 0.00		≈ 0.00	
M	Mass of Concrete. *lbs*		1200.69		7.37		1051.27	
V	Absolute Volume of Concrete, ft^3		24.05		0.15		21.06	
T	Theorectical Density, lb/ft^3 = *(M / V)*		49.92		49.33		49.92	
D	Design Density, lb/ft^3 = *(M / 27)*		44.47					
D	Measured Density, lb/ft^3				37.300		37.300	
A	Air Content, *%* = *[(T - D) / T x 100%]*		10.91		24.38		25.28	
Y	Yield, ft^3 = *(M / D)*		**27**		0.1976		**27**	
Ry	Relative Yield = (Y / Y_D)				1.142			

Mixture ID: Hull/Patch				Design Proportions (Non SSD)		Actual Batched Proportions		Yielded Proportions	
Y_D	Design Batch Size (ft^3):	0.173							
Cementitious Materials			SG	Amount (lb/yd^3)	Volume (ft^3)	Amount (lb)	Volume (ft^3)	Amount (lb/yd^3)	Volume (ft^3)
CM1	White Portland Cement		3.15	382.22	1.945	2.45	0.012	318.47	1.620
CM2	White Silica Fume		2.20	22.48	0.164	0.14	0.001	18.73	0.136
CM3	Metakaolin		2.60	71.15	0.439	0.46	0.003	59.28	0.365
	Total Cementitious Materials:			475.85	2.55	3.05	0.016	396.48	2.12
Fibers									
F1	PVA		1.30	28.34	0.349	0.18	0.002	23.61	0.291
	Total Fibers:			28.34	0.35	0.18	0.002	23.61	0.29
Aggregates									
A1	3M™ K15	Abs: 0 %	0.15	76.51	8.174	0.49	0.052	63.75	6.811
A2	3M™ S38HS	Abs: 0 %	0.38	129.22	5.450	0.83	0.035	107.67	4.541
	Total Aggregates:			205.73	13.62	1.32	0.087	171.42	11.35
Water									
W1	Water for CM Hydration (W1a + W1b)		1.00	393.25	6.302	2.52	0.040	327.66	5.251
	W1a. Water from Admixtures			393.25		2.52		327.66	
	W1b. Additional Water			0.00		0.00		0.00	
W2	Water for Aggregates, SSD		1.00	0.00		0.00		0.00	
	Total Water *(W1 + W2)* **:**			393.25	6.30	2.52	0.040	327.66	5.25
Solids Content of Latex Admixtures and Dyes									
S1	Latex (if used)		1.10	74.76	1.089	0.16	0.002	62.29	0.908
	Total Solids of Admixtures:			74.76	1.09	0.16	0.002	62.29	0.91
Admixtures (including Pigments in Liquid Form)			% Solids	Dosage (fl oz/cwt)	Water in Admixture (lb/yd^3)	Amount (fl oz)	Water in Admixture (lb)	Dosage (fl oz/cwt)	Water in Admixture (lb/yd^3)
Ad1	Silpro C-21 Latex	*9.2 lb/gal*	20%	1095.38	373.07	10.95	2.39	912.7	310.85
Ad2	ADVA Cast 575®	*8.9 lb/gal*	40%	21.85	7.20	0.22	0.05	18.2	6.00
Ad3	Eclipse® Floor 200	*7.9 lb/gal*	1%	44.17	12.97	0.44	0.08	36.8	10.81
	Water from Admixtures *(W1a)* **:**				393.25		2.52		327.66

		Design Proportions	Actual Batched Proportions	Yielded Proportions
	Cement-Cementitious Materials Ratio	0.803	0.803	0.803
	Water-Cementitious Materials Ratio	0.70	0.70	0.70
	Slump, Slump Flow, *in*.	3.00 ± 1	3.00 ± 1	3.00 ± 1
M	Mass of Concrete. *lbs*	1177.93	7.23	981.46
V	Absolute Volume of Concrete, ft^3	23.91	0.15	19.92
T	Theorectical Density, lb/ft^3 = *(M / V)*	49.26	48.65	49.26
D	Design Density, lb/ft^3 = *(M / 27)*	43.63		
D	Measured Density, lb/ft^3		34.800	34.800
A	Air Content, % = *[(T - D) / T x 100%]*	11.44	28.47	29.36
Y	Yield, ft^3 = *(M / D)*	**27**	0.2076	**27**
Ry	Relative Yield = (Y / Y_D)		1.200	

APPENDIX C—BILL OF MATERIALS

Material	Quantity		Unit Cost	Total Price
Cementicious Material				
White Portland Cement, Type I	55.92	lb	$ 0.28	$ 15.66
White Silica Fume	3.29	lb	$ 1.11	$ 3.65
Metakaolin	10.41	lb	$ 0.75	$ 7.81
Aggregates				
K-15	11.14	lb	$ 12.50	$ 139.25
S38HS	18.8	lb	$ 6.87	$ 129.16
Fibers				
PVA Fibers	5.02	lb	$ 8.00	$ 40.16
Admixtures				
SilPro C-21 Latex	5.8	gal	$ 18.00	$ 104.40
Eclipse SR	32.16	fl oz	$ 0.08	$ 2.57
ADVA Cast 575	18.88	fl oz	$ 0.09	$ 1.70
Reinforcement				
Fiberglass Mesh	74.22	sq ft	$ 0.04	$ 2.97
Carbon Fiber Mesh	40.75	sq ft	$ 0.03	$ 1.22
Post Tensioning System	1	lump sum	$ 33.64	$33.64
Construction Mold				
XPS Foam (4'x8'x2")	8	sheet	$ 30.00	$ 240.00
Plywood (8'x4'x1/2")	6	sheet	$ 24.00	$ 144.00
Plaster	3	lb	$ 0.66	$ 1.98
Polystyrene Spray Adhesive	5	can	$ 15.00	$ 75.00
Release Agent	0.25	gal	$ 25.00	$ 6.25
Finish				
Water Based Stain	0.5	gal	$ 40.00	$ 20.00
Sealer	0.5	gal	$ 25.00	$ 12.50
Sanding Paper (various grits)	1	lump sum	$ 500.00	$ 500.00
Vinyl Lettering	1	lump sum	$ 300.00	$ 300.00
Total Cost				
			Total Cost	$ 1,481.92
			Donated	$ 627.30
			Actual Cost	**$ 854.62**