2015 Concrete Canoe Design Paper

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Executive Summary

America in the 1950s was a time of unprecedented turbulence. Post World War II politics and fundamental differences in ideological viewpoints led to the birth of the Cold War. The Civil Rights Movement finally began to take stride as non-violent civil protesters put their safety on the line in their fight against unconstitutional laws and discrimination. The United States of America and the Soviet Union began a race to the Moon after the launch of the Soviet-made *Sputnik* in 1957.

Amongst high tensions, the fight for equality, and a virulent contest in engineering prowess, Americans still found time to relax and indulge their interests thanks to an improving economy. For those who relished the challenge of creating a finely tuned, custom-built automobile, the world of the American hot-rod proved irresistible. As the economy began an upward trajectory hot-rodding followed suit, flourishing into a treasured American past-time. The University of Massachusetts Lowell Concrete Canoe Team seeks to channel the historical passion of 1950s hot-rodding to produce a beautifully sleek and well-designed racing machine—*Backfire*—named in deference to the unpredictable struggles of developing a truly unique creation, and in honor of the perseverance that must overcome that struggle.

UMass Lowell has undergone tremendous amounts of change over the years. Originally two separate institutions in the city of Lowell, Massachusetts, the liberal arts Lowell State College and the engineering centric Lowell Technological Institute merged to form the University of Lowell in 1975. In 1991, the University of Lowell was absorbed into the UMass system and UMass Lowell as it is known today was born.

Comprised of 17,000 undergraduate and graduate students in six schools and colleges, Lowell offers over 150 fully accredited academic programs. UMass Lowell's Francis College of Engineering has earned its reputation as an applied research institution, from its on-campus nuclear research reactor to its Major League Baseball funded UML Baseball Research Center.

Table 1. *Backfire* Specifications

Estimated Weight	130 lbs
Length	19 ft. 10 in.
Maximum Beam	27 inches
Depth	13.9 inches
Thickness	3/8 in. (Average)
Color	Red, Tan, Gray
Reinforcement	Fiberglass Mesh Carbon Fiber Mesh Galvanized Steel Cable

Table 2. Concrete Properties

Plastic Unit Weight	44.3 pcf
Oven-Dried Unit Weight	40.5 pcf
28-day Compressive Strength	1,800 psi
28-day Tensile Strength	390 psi
Young's Modulus	111.6 ksi
Modulus of Rupture	239 psi
Concrete Color	Light Gray

Building upon innovations from the 2014 season, Lowell sought to refine methods used in the past to create a more sustainable final product. Hull design processes were further developed to create a hull with maneuverability, speed, and stability equally weighted (specifications shown in Table 1). A more comprehensive two-dimensional analysis which utilized failure theories of advanced mechanics of materials was conducted. Further research into the behavior of hydraulic cement hydration and natural cement carbonation resulted in a final mix design capable of withstanding all the rigors of competition (Table 2). The application of an automated misting system in lieu of humidifiers kept water and electrical consumption to a minimum during the construction process. Lowell's innovative cooling system (*Vanguard,* 2014) was redesigned to more effectively minimize heat of hydration. In addition to improvements and innovations, Lowell aimed to teach new members techniques through the construction of a newly-designed practice canoe—*Lead Sled* (Lěd-Slěd)—and the documentation of the full design and construction process.

Lowell's management team was restructured to avoid the overload of any one person. Two Co-Project Managers alongside a Field Manager split the tasks of budgeting, scheduling, and oversight of the day-to-day operations. Additionally, a Sustainability Officer was introduced this year to analyze the team's impact on the environment and to seek out ways to limit it.

UMass Lowell has appeared annually in the New England Regional Competition (NERC) since its 2009 entry, *Merrimack Maiden*. In the past three years, Lowell has placed consistently high at the NERC—placing 2nd in 2012 with *Revolution*, 1st in 2013 with *Moswetuset*, and 2nd in 2014 with *Vanguard*.

Hoping to repeat the success of previous years, *Backfire* represents Lowell's vision for a 1950s style hot-rod—a purely unique, extremely capable competitor that is truly one of a kind.

Project Management

Due to the continued success of the existing system, the managerial structure for Lowell functioned much the same as in past years and underwent only minimal changes. Following the 2014 season, two co-Project Managers, a Field Manager, four team captains, and three officers were selected to manage various aspects of the team's 2015 entry. In order to allow flexibility within the management structure, the team elected to have two experienced members act in the project management role rather than one. The pair worked with members and advisors to schedule team meetings, promote team activities, and manage fiscal matters.

Each team captain directed one of four project subdivisions: hull design and structural analysis, mix development and testing, construction and aesthetics, and paddling. Innovation and research were emphasized in all phases of the project. A detailed schedule earmarked time for the evaluation of possible project innovations while ensuring that the team met the milestone deadlines along the critical path as shown in Table 3. A margin of error was utilized which minimized the impact of the unexpected weather conditions during the New England winter, ensuring that each milestone would be met before the project deadline.

Table 3. Major Project Milestones

Milestone	Proposed	Actual	Reason for Variance
Hull Design Selection*	9/26/14	9/26/14	-
Structural Analysis	10/15/14	10/18/14	Resources Allocated to Mold Construction
Lead Sled Placement Day*	12/5/14	12/5/14	-
Backfire Mix Selection	1/20/15	1/29/15	Multiple Blizzards
Backfire Placement Day*	1/25/15	2/5/15	Multiple Blizzards
Backfire Finishing*	4/5/15	NA	-
Design Paper Submission	3/19/15	3/19/15	-

***Denotes Critical Path**

Backfire's team was comprised of 22 members accumulating an estimated total of 4,675 person-hours (Figure 1), representing a decrease in the amount of time worked on *Backfire* versus *Vanguard* by 9%. This reduction in person-hours can be attributed to better time management and the refinement of construction techniques over the years.

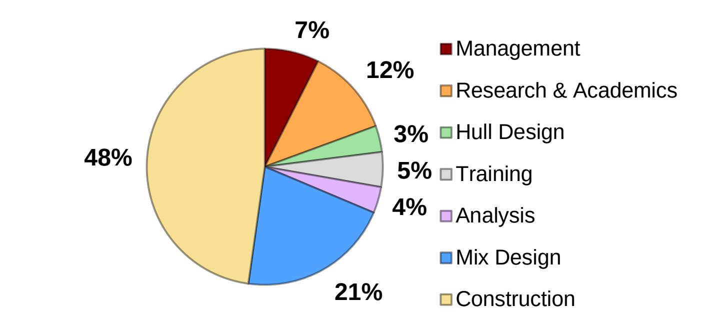


Figure 1. Person-Hour Allocation

An experienced team member was selected to act as *Backfire*'s Safety Officer and tasked with researching safe construction and lab processes before instructing the rest of the team on safety rules. To develop construction expertise among team members a practice canoe dubbed *Lead Sled*—a term describing low-slung hot-rods from the 1950s—was fabricated in lieu of *Backfire*'s originally planned placement day. When time came to place *Backfire*, all members were already familiar with their roles in the process, resulting in a smoothly run five-hour day of work.

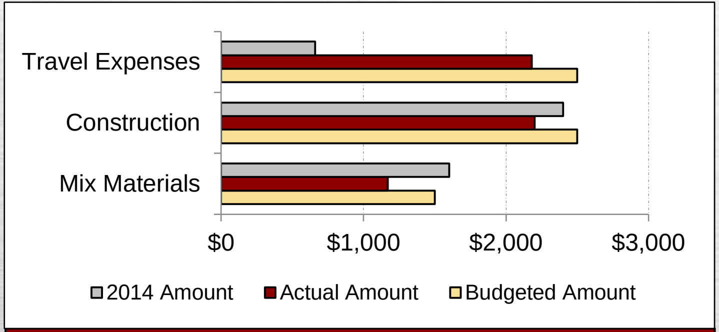


Figure 2. Project Expenses

Backfire's financial plan was based upon previous experience, with the operating budget set at $6,500—which includes the cost of mix materials, construction materials, and conference travel expenses. A breakdown of the allocation of funding compared to budgetary constraints and the 2014 season's expenses can be seen in Figure 2. Proper budgeting, material donations, as well as refurbishing various construction materials brought the total cost of the project to $5,550, a full $950 under budget.

Throughout all phases of the project, team members were kept up to date via email and scheduled meetings. Particular attention was paid to the recruitment and integration of new members. School functions, class meetings, and student organizations were used as conduits for promoting the team and encouraging participation among peers. Capitalizing on the varied characteristics and skills among the newest team members, team captains assigned tasks accordingly. *Backfire* benefitted greatly from the dedicated work of team members who were allowed to specialize in their area of interest.

Organization Chart

Maureen Kelly · Ryan Walker — Co-Project Managers

Responsible for budgeting, fundraising, material procurement, student government relations, business outreach, member recruitment, and setting critical path deadlines.

Jonathan Nadeau — Field Manager

Responsible for managing captains, scheduling, process documentaition, and overseeing daily operations.

Nicholas Brisbois — Design and Analysis Captain

Responsible for designing the hull, computer modeling, classical two-dimensional analysis, and structural elements design.

Hull Design and Structural Analysis Team

Junior Captain: Cynthia Chestnut

Members: Patrick Raistrick
Jonathan Nadeau

Patrick Raistrick — Mix Design Captain

Responsible for mix research and innovations, material selection, initial and final testing, and sample placement.

Development and Testing Team

Junior Captain: Rebecca Gonsalves
Members: Jeff Beck
Jeffrey Bruso
Jonathan Nadeau
Zachary McDonough

Jesse Merchant — Paddling Captain

Responsible for coordinating practices, conditioning paddlers, and coaching proper paddling technique.

Paddling Team

Junior Captain: Justin O'Connor
Members: Cynthia Chestnut
Danielle DeWolf
David Salyer
Jeff Beck
Maureen Kelly
Taylor Moylan

Members

Name	Year	Years Involved	Active Participant
Joseph Benoit	Grad	5	3
Jesse Merchant	Sr	4	3
Cassandra Piorkowski	Grad	3	2
Jeffrey Bruso	Grad	3	0
Jonathan Nadeau	Grad	3	0
Mark Procopio	Grad	3	0
Maureen Kelly	Sr	3	3
Patrick Raistrick	Grad	3	2
Nicholas Brisbois	Grad	2	0
Rebecca Gonsalves	Jr	2	2
Ryan Walker	Sr	2	0
Zachary McDonough	Jr	2	1
Christopher Cantin	Fr	1	0
Cynthia Chestnut	Fr	1	1
Danielle DeWolfe	Sr	1	1
David Salyer	Sr	1	1
Ian Sherriff	Fr	1	0
Jeff Beck	Fr	1	1
Justin O'Connor	So	1	1
Nicholas Stillwell	Fr	1	0
Shiv Bhardwaj	Fr	1	0
Taylor Moylan	Sr	1	1

Faculty Advisor: Gary Howe

Zachary McDonough — Construction and Aesthetics Captain

Responsible for construction and finishing of the mold, canoe, aesthetic elements, stand, sectional, and display.

Construction Team

Junior Captain: Jeff Beck
Members:
Cassandra Piorkowski
Christopher Cantin
Cynthia Chestnut
Ian Sheriff
Jeffrey Bruso
Jesse Merchant
Jonathan Nadeau
Justin O'Connor
Mark Procopio
Maureen Kelly
Nicholas Brisbois
Nicholas Stillwell
Patrick Raistrick
Ryan Walker
Shiv Bhardwaj

Aesthetics Team

Members: Cynthia Chestnut
Jonathan Nadeau
Maureen Kelly
Nicholas Brisbois
Patrick Raistrick
Rebecca Gonsalves
Ryan Walker

Jeffrey Bruso — Safety Officer

Responsible for updating MSDS, ensuring proper PPE usage, and instructing safety sessions.

David Salyer — Sustainability Officer

Responsible for overseeing the team's economic and environmental impact and how to reduce it.

Mark Procopio — Quality Control Officer

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

Hull Design and Structural Analysis

Hull performance is broken down into three basic categories: maneuverability, speed, and stability. Lowell's 2012 entry *Revolution* possessed straight-line speed with good stability. However, its maneuverability was poor due to its drastic asymmetrical design. 2013 responded with *Moswetuset*, featuring a hull designed with maneuverability as a dominant trait. Though capable of high speeds, *Moswetuset* lacked stability. Lowell's 2014 canoe, *Vanguard*, excelled in stability while retaining both respectable speed and maneuverability. This year by fine tuning each category and using *Vanguard* as a baseline hull in Prolines© 7, Lowell created *Backfire*'s racing hull with each category evenly weighted. A visual representation of Lowell's idealized hull design is shown in Figure 3.

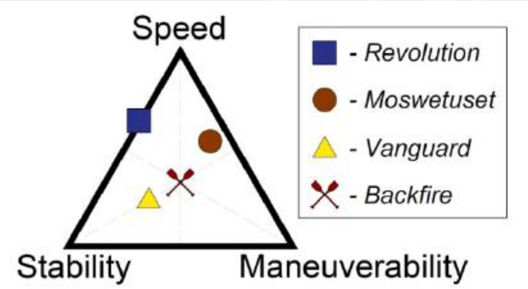


Figure 3. Idealized Hull Design

Lowell began the design process by analyzing both *Moswetuset* and *Vanguard*. It was determined that adjusting the rocker of a canoe had a dramatic effect on its ability to turn. It was also noted that *Vanguard*'s V-notched bow considerably increased tracking ability. Taking these factors into consideration, *Vanguard*'s V-notched bow was utilized and the bow rocker was increased. This approach decreased impeded lateral water flow, allowing the hull to track effectively in a straight line as well as pivot around turns. Turning resistance was further reduced by decreasing *Backfire*'s length in relation to *Vanguard*, resulting in better maneuverability.

In previous years, the primary design factor for Lowell was speed. However, by practicing with paddlers in various canoes, it was apparent that the maximum speed of each hull was approximately the same—with the change in performance stemming from initial acceleration. Acceleration is affected by hull resistances and the weight of the canoe itself. The waterline length was reduced by increasing the bow rocker of the canoe to lift the bow out of the water during two-paddler races. This design reduced both bow wave drag and the wetted hull surface area—the two major resistances in hull design. Calculations using a maximum sustained speed of 9 ft/s revealed a significant decrease in wave drag due to the planing bow.

The stability of a canoe is directly correlated to the shape of the hull bottom and sidewalls. A flat bottom results in high initial stability, giving the vessel a natural tendency to remain parallel to the water surface while moving at slow speeds. Conversely, secondary stability describes the steadiness of a hull while moving quickly. Because *Backfire* was designed to be a competitive racer, initial stability was not considered the primary stability state. By slightly curving the base of the hull, higher secondary stability was achieved (*Randall,* 2010). Since high secondary stability was desired, a slightly round bottom aft of the bow paddler, similar to *Revolution*, was chosen. Focus then shifted to the other stability-determining factor, sidewall design. To further increase secondary stability, the team chose to use flared sidewalls in conjunction with a tumblehome shape just below the gunwales at mid-span for more efficient paddle strokes. In addition to an improved hull shape, the freeboard for *Backfire* was increased to nearly one inch more than *Vanguard* to alleviate noted stability loss with 4-paddler races in the 2014 season.

Lowell's previous three competition canoe designs were then compared to *Backfire* as seen in Table 4. Key parameters were changed to increase Backfire's maneuverability and stability. However, values for prismatic coefficient, which determines a shape's submerged "fullness," did not drastically increase in comparison to Vanguard. This approach created a fast, stable, and maneuverable hull design for *Backfire*.

Table 4. Design Parameters for Two-Male Loading

Canoe Name	*Revolution*	*Moswetuset*	*Vanguard*	*Backfire*
Canoe Weight	208 lb	132 lb	115 lb	130 lb
Overall Length	235 in	236 in	243 in	238 in
Load Waterline Length, LWL	238 in	236 in	244 in	221 in
Beam Waterline Length, BWL	23.5 in	24.6 in	26.5 in	26.8 in
Maximum Depth	14.9 in	13.5 in	12.8 in	13.9 in
Freeboard	9.58 in	7.86 in	7.56 in	8.44 in
Bow Rocker	5.0 in	3.0 in	3.3 in	6.4 in
Stern Rocker	2.0 in	4.5 in	4.3 in	4.3 in
Wetted Hull Surface Area	34.7 ft^2	31.8 ft^2	32.4 ft^2	31.4 ft^2
Prismatic Coefficient, C_p	0.545	0.434	0.441	0.468
Wave Drag at 9 ft/s	14	10.75	9.25	6.75

Lowell decided to analyze *Backfire* in two different orientations—longitudinally and transversely. With this in mind, Lowell applied failure theories of advanced mechanics of materials in order to ensure a comprehensive analysis.

The team chose to consider six loading scenarios for *Backfire*'s structural analysis: two-male loading, two-female loading, four-paddler loading, two-person carry, static display, and hydrostatic transverse. Competition transportation loading was not considered, as *Backfire* was completely supported during such movement. After analyzing these scenarios, it was determined that the highest bending moment occurred during the two-male loading case while static display loading governed transverse analysis.

As such, *Backfire* was modeled as a simply supported beam with varying cross sectional data that was subjected to symmetrical bending about the X-axis. Gunwales were added to *Backfire*'s design to increase inertia about this axis. Magnified knee loads of 165 lbs and 185 lbs were applied at 45 inches and 200 inches aft of bow, producing the critical bending moment envelope shown in Figure 4. Maximum tensile and compressive bending stresses were then calculated at critical locations using Equation 1.

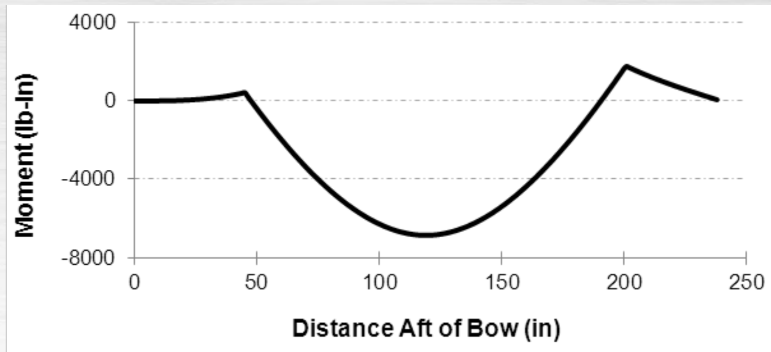


Figure 4. Critical Moment Envelope (Two-Male Loading with Gunwales)

$$f_b = \frac{M_{max}c}{I_x} \qquad \text{(EQ 1)}$$

Ultimate stress values were found to be at 116 inches aft of bow, with extreme fiber distances of c_t = 8.48 inches and c_c = 5.42 inches being used to calculate the ultimate tensile and ultimate compressive stresses within the section respectively as shown in Table 5 below. I_x was hand calculated as shown in Appendix D and verified using AutoCAD.

A dynamic loading amplification factor (DAF) of 1.25 (*Paradis,* 2007) as well as a mix design factor (MDF) of 2.5 were applied to maximum bending stresses to account for various factors outside the scope of this analysis. By plotting these magnified stresses alongside *Backfire*'s failure envelope as shown in Figure 12 (Development and Testing, Page 7), it was clear that *Backfire* would be strong enough to withstand all combinations of tension, compression, and shear.

The static display load case, which can be described as the position of the canoe while on display in its stand, was found to be the most critical transverse analysis case for *Backfire*. Lowell's Construction and Aesthetics team included three structural ribs, spaced 28 inches on center from mid-span outward, and the task fell to the analysis team to ensure that transverse deflection was limited to a maximum of 1/8 inch per rib using principles of statics and pure bending mechanics.

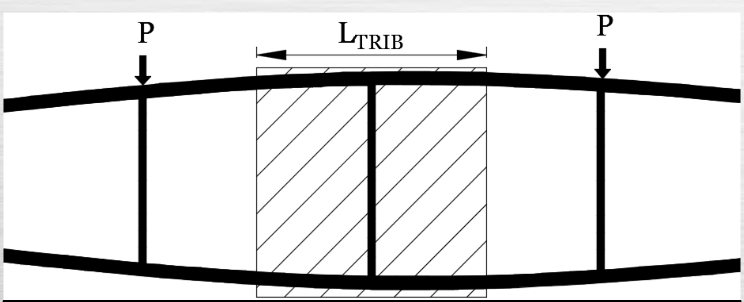


Figure 5. Free Body Diagram for Rib Analysis

A free body diagram describing the loading for transverse static display is shown in Figure 5. Rib dimensions were assumed for trial calculations and adjusted based upon the limitations of available cutting equipment. Moments of inertia (I_y) of these new cross sections were then determined by a process similar to that used for I_x values. Tributary lengths (L_{trib}) were assigned to each rib, two service point loads of 65 lbs (P) were applied at outer rib locations, and required Young's Modulus ($E_{req'd}$) was calculated using Equation 2.

$$E_{req'd} = \frac{PL_{trib}{}^3}{28\Delta_{max}I_y} \qquad \text{(EQ 2)}$$

The results of Lowell's structural analysis of *Backfire* are shown in Table 5. A simplified analysis demonstrating Lowell's ability to conservatively calculate these requirements is shown in Appendix D.

Table 5. Structural Demand for *Backfire*

Parameter	Demand (psi)
Tensile	160
Compression	102
Young's Modulus (E)	816

Development and Testing

The placement of *Lead Sled* in early December functioned as an opportunity to test a variant of the concrete used for *Backfire*. To secure the advantages of early testing and selection, the mix design team was required to operate within a shortened testing period. With this in mind it was determined that Lowell would have to rely heavily upon previous research into aggregate gradation (*Moswetuset,* 2013) and bond strength (*Vanguard,* 2014) in order to develop a strong, lightweight, and sustainable mix in such a short amount of time.

A magnified tensile stress of 160 psi was considered the governing stress in the canoe per *Backfire*'s analysis team. As such, *Vanguard*'s structural mix design (41.1 pcf, 240 psi tensile strength, w/cm 0.6, 2.00% PVA, and optimized cement matrix) served as the baseline for the newly implemented iterative design approach as shown in Figure 6.

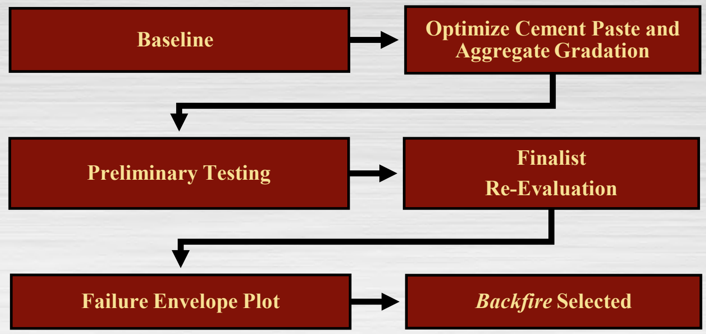


Figure 6. Iterative Design Approach

Beginning with cement paste optimization, Lowell investigated the use of various natural cementing agents, with the primary binder under consideration being Rosendale cement. Natural cements behave differently than hydraulic cements during the curing process, with natural cements undergoing carbonation whereas hydraulic cements undergo hydration. Carbonation is a process in which carbon dioxide (CO_2) is emitted slowly as an intermediary product, with the cured product being calcium carbonate ($CaCO_3$) as shown below in Table 6, Equations 1 and 2 (*Development and Testing*, Page 6). Calcium carbonate acts as a long-term storage tank for the produced carbon. This stored carbon slowly emits into the environment over time, potentially increasing the environmental footprint of *Backfire* considerably. Furthermore, carbonation is a much slower process than hydration—with the former being linear and taking three times as long to reach desired strength levels in testing as shown in Figure 7. In order to acquire a higher strength in natural cement mix design, pozzolanic materials can be introduced. However, hydrated lime (CH)—a rather unsustainable material to produce—is required to facilitate the pozzolanic reaction. Although hydrated lime is produced naturally during carbonation, it is required to complete the final carbonation reaction and cannot be used as a limiting reagent. For these reasons it was determined that a hydraulic cement binder comprised of portland cement and environmentally friendly pozzolans would be utilized to decrease emissions during construction and ensure a more consistent final product (*Mindess*, 2003).

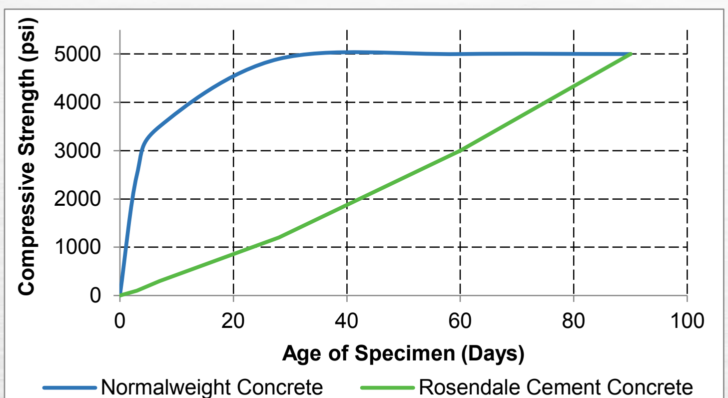


Figure 7. Compressive Strength Gains over Time (Data Courtesy of *Edison Coatings, Inc.*)

Since the bond strength of portland cement based concrete is directly related to the hydration of portland cement, *Backfire*'s concrete mixture was developed by determining how much calcium-silicate-hydrate (C-S-H) gel—the source of concrete's bond strength—and hydrated lime are created during the hydration reactions of belite (C_2S) and alite (C_3S). This can be seen in Table 6, Equations 3 and 4 (*Development and Testing*, Page 6).

Hydrated lime is hydrophilic and as a result only weakens concrete over time. In a poorly proportioned matrix, hexagonal hydrated lime crystals stack upon each other, causing relatively large weak zones in concrete. Conversely, in an ideal matrix, pozzolanic filler and colloidal C-S-H gels fill the voids instead of hydrated lime, increasing overall strength in these areas. Lowell minimized the impact of hydrated lime on *Backfire*'s final mix design by using the volumetric combination of 78% type I white portland cement, 19% high-reactivity metakaolin, and 3% silica fume for its cement matrix. These proportions were perfected by taking the hydrated lime created from the hydration process and using it as the limiting reagent for the pozzolanic reaction (Table 6, Equation 5) taking into consideration both the molar weights and percentage by volume of each constituent material involved in the hydration process. *Lead Sled*'s mix was comprised of a similar cement matrix; consisting of 77% type I white portland cement, 17% high-reactivity metakaolin, and 6% silica fume. A comparison of a high hydrated lime content cement matrix versus an ideal one is shown in Figure 8.

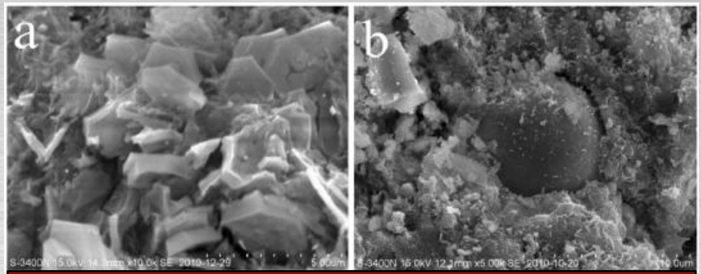


Figure 8. Comparison of High Lime Content Matrix (Left) and Ideally Proportioned Matrix (Right) (*Liu et. al.*, 2014)

It should be noted that in addition to facilitating the pozzolanic reaction, high-reactivity metakaolin content was increased for *Backfire* due to 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 7.

Table 6. Chemistry of Carbonation and Hydration

Carbonation Reactions	
Intermediary	$CaCO_3 + \text{HEAT} \rightarrow CaO + CO_2$ (EQ 1)
Final Product	$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$ (EQ 2)
Hydration Reactions	
Belite	$2C_2S + 7H_2O \rightarrow C-S-H + CH$ (EQ 3)
Alite	$2C_3S + 5H_2O \rightarrow C-S-H + 3CH$ (EQ 4)
Pozzolanic Reaction	
Pozzolanic Reaction	$Pozzolan + CH \rightarrow C-S-H$ (EQ 5)

Building upon previous research performed for *Moswetuset* on the topic of aggregate gradation in concrete, *Backfire*'s mix design team chose to utilize a combination of all fine aggregates. 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. Previous testing had shown that a gap graded aggregate distribution of approximately 4:1 K15 to S38HS would prove sufficient in maximizing the bonding surface area of concrete mixtures. By decreasing hydrated lime content in the cement matrix while holding this aggregate gradation constant, stresses were decreased within the interfacial transition zone (ITZ)—concrete's tensile failure zone—by allowing more bonding potential due to increased C-S-H content (*Kosmatka*, 2011).

Table 7. Pozzolan Properties and Benefits

Pozzolan	Molar Weight	Potential Benefits
Silica Fume	60 g/mol	Low molar weight, void filler, high aesthetic quality
High Reactivity Metakaolin	223 g/mol	Deters ASR, good for "fine tuning" CH content
Pumice Powder	72 g/mol	Natural shrinkage reducer
Fly Ash	77 g/mol	Increases durability and workability

Backfire's mix was designed to withstand all stresses on its own without flexural reinforcement, save for a 2% by volume matrix of 3/8 inch polyvinyl alcohol (PVA) fibers added directly to the mix itself. A combination of fiberglass and carbon fiber meshes were added as an extra factor of safety to increase flexural resistance in the placed product (*Construction*, Page 9).

Figure 9. Shotcrete Sprayer

Furthermore, Eclipse® Floor 200 Shrinkage Reducer and ADVA® Cast 575 Super Plasticizer were used at manufacturer's minimum 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 of 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.

During initial design, Lowell outlined a process for the use of shotcrete on placement day using a custom made shotcrete sprayer as shown in Figure 9. The sprayer was built late in the 2014 season using scrap parts from previous projects, incurring no additional cost or material waste for the year. The gun consists of a piston style hopper with a pressure plate uniformly distributing 10 psi of compressed air to the entire hopper down to the nozzle. The nozzle is then pressurized with an additional 10 psi of compressed air to force the concrete to flow, with pressure regulators allowing for spraying adjustments as needed. It was determined that high volume/low pressure gunning of concrete mixtures provided higher compaction and noticeably better fiber alignment on sample shotcrete panels versus hand placed panels. However, the appropriate testing of these samples would incur too high of a cost since a coring drill is required to obtain representative test specimens (ASTM C1604). Unable to expense the cost of such a drill, Lowell opted to abandon shotcrete for more practical, economical, and consistent methods of placing and testing.

Before preliminary testing began, *Backfire*'s Safety Officer performed an inspection of Lowell's Concrete Research Laboratory in order to ensure that all equipment was safe for use. This inspection consisted of posting material safety data sheets (MSDS) and ensuring that personal protective equipment (PPE) was available for all members of the team. Additionally, *Backfire*'s Quality Control Officer checked material expiration dates, hand sieved portland cement, and ensured that all mix containers and tools were free of outside contaminants. Once these checks were performed, the mix design team initiated its first rounds of testing.

Focusing on minimal downtime during preliminary testing rounds, Lowell chose to utilize an accelerated steam curing cycle that was implemented in the 2014 season. This standardized steam curing cycle allowed Lowell to test samples with relative 28-day maturity after just 18 hours of curing (*Mindess,* 2003). Due to the small size of the steam bath (shown in Figure 10) and to save on material cost, 2x4 cylinders were used instead of 3x6 cylinders for initial testing in tension (ASTM C496) and compression (ASTM C39). The use of these cylinders decreased Lowell's environmental footprint for the year greatly with the 2x4 cylinders requiring about 1/5 of the materials necessary for testing. Additionally, 12 inch x 6 inch x 3/8 inch flexure beams were tested using third point bending (ASTM C1609).

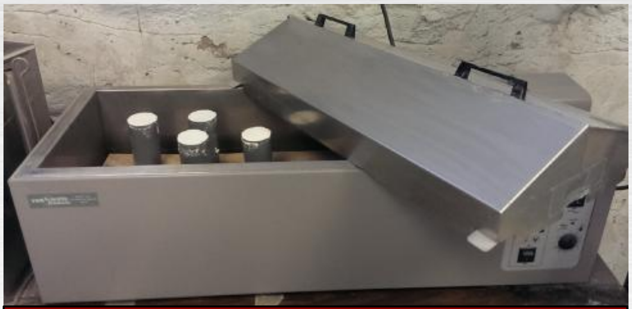


Figure 10. Accelerated Curing Steam Bath

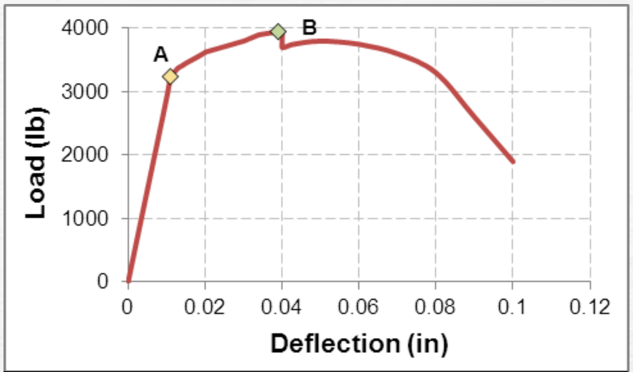


Figure 11. Flexural Loading Curve

Taking into consideration the results shown in Figure 11 from flexural loading data (ASTM C1609), it was determined that Lowell's flexural strength would be taken as the point where the ITZ of the specimen has begun to fail and the PVA matrix starts to receive loading (Point A). This approach prevents visible cracking which would eventually cause failure at the peak loading (Point B). After this point, the specimen will continue to undergo strain due to the residual strength of the PVA matrix before giving out completely.

Finalists were re-evaluated using 3x6 cylinders and a standardized 21-day moist curing system using the same methods of testing as preliminary rounds. Final engineering properties for *Backfire* were determined from 3x6 cylinders and 12 inch x 6 inch x 3/8 inch flexure beams cast on placement day. Young's Modulus was derived using ASTM C469. 28-day tensile and compressive strengths for *Backfire* were used to formulate a failure envelope using Mohr's Failure Theory (*Beer*, 2012) and plotted against the Mohr's stress circle as shown in Figure 12. A summary of these tests are compared to Lowell's previous five canoes in Table 8.

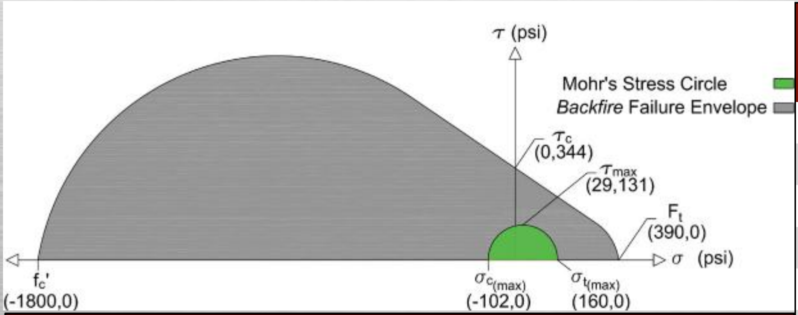


Figure 12. Mohr's Failure Envelope Plot

Table 8. Comparison of Lowell Mixes

Canoe	w/cm	%CP	Unit Wt. (pcf)	Capacity (psi) Tension	Capacity (psi) Compression
Backfire	0.65	40%	40.5	390	1800
Lead Sled	0.7	35%	39.9	290	1270
Vanguard	0.6	35%	41.1	240	1158
McPortland	0.65	45%	50.4	490	2750
Moswetuset	0.7	40%	44.6	315	1436
Revolution	0.7	45%	52.0	520	2980

Construction

After the 2014 season, Lowell's construction team lost multiple key veteran members. To account for these losses, the management team allowed more time for the refinement of innovations and improvement of team coordination. By contacting returning team members during the summer months, the construction team was able to prepare for placement day in early December. This very early placement was made possible due to refined processes developed in recent years.

Following the release of the 2015 NCCC Rules and Regulations, the construction team began work on the male mold, chosen for its time-tested ease of construction and superior finishing results. With the design and analysis team providing two-inch interval paper cross-sections, *Backfire*'s computer model was transferred onto two-inch thick extruded polystyrene (XPS) foam pieces. XPS foam was chosen for both its ability to support the construction process and to utilize the recycling of sections from *Vanguard*'s mold.

At this point in the season, the team began to capture the interest of new members. With the majority of the construction team comprised of freshmen, the management team allotted more time for members to gain experience. It was determined that the best option was the placement of a practice canoe using surplus materials. This was beneficial in two ways: members were prepared for the placement of the competition canoe and a replacement was built for the practice canoe made last year, which developed severe cracking during transportation to practice. Originally scheduling placement in December allowed for plenty of time to place another canoe at the beginning of the new year.

As such, Lowell began work on the new practice canoe, *Lead Sled*, using the templates previously created by the design and analysis team. *Lead Sled*'s mix was a variant of *Backfire*'s design—a lightweight mix designed to work in conjunction with an outer fiberglass layer to prevent the cracking issues seen in *McPortland*, the practice canoe from the previous year.

After *Lead Sled* cured, focus was set on mold construction for *Backfire* in January. Looking for other mold construction methods so that the team could begin work on the display and stand, Lowell attempted to locate a CNC machine capable of milling the new mold. Unable to track down a suitable CNC machine, it was determined that the mold would be hand constructed for *Backfire*. The team acquired additional XPS foam to replace the few unrecyclable sections removed from *Lead Sled*. Mold sections were hand cut with a band saw and glued together. Three sections received routed ribs, which were spaced 28 inches apart to accommodate paddler ergonomics. *Backfire*'s mold was then sanded into shape. Gunwales were then cut into the mold using a foam-cutting hot knife guided by a track system, providing a consistent gunwale shape from bow to stern. Aesthetic 3D elements inspired by automotive designs of the 1950s were then imprinted into the mold using a combination of a router and hand carving.

Continuing the research done for *Vanguard*'s highly effective cooling system, *Backfire*'s team further improved upon its innovation. The cooling system was developed last year to aid in keeping the concrete both continuously moist and cool. Recycling the system used for *Vanguard*, a series of 3/8 inch wide channels were routed into the top and sides of the mold, lined with vinyl tubing, and connected to a pump that kept a glycol solution flowing throughout the mold. Improvements were added to the system including the introduction of a radiator, a temperature controlled fan, and an inline temperature sensor. By locating the fluid basin outside, the cooling system took advantage of the New England winter to cool the glycol solution. By temperature controlling the fluid, the system ensured that the surface of *Backfire* would maintain a constant 5º F cooler than the ambient temperature, as measured by a thermal imaging camera. The resulting image is shown in Figure 13. The channels of the cooling system and other slight imperfections were smoothed over with joint compound to give *Backfire*'s inner hull a perfect shape. This cooling system reduced initial air entrainment loss, microsphere aggregate expansion, and heat shrinkage cracking for the first seven days of the curing cycle, preventing negative effects caused by the high early heat of hydration of concrete.

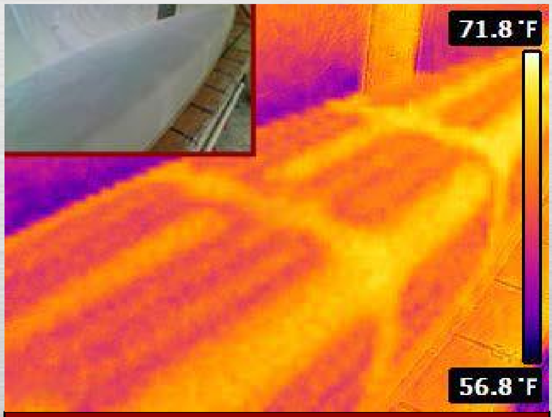


Figure 13. Cooling System Thermal Image

Following the introduction of a Sustainability Officer, Lowell focused on reducing its environmental and economic impact during the construction process. With new ideas for reduction of waste and increasing environmentally friendly practices, the team followed guidelines to keep excess to a minimum. This began by recycling the hydration tent used in previous years to provide a humid environment to keep the concrete workable for the entire placement. The team also affixed a newly designed automated misting system, replacing the previously used humidifiers for time management concerns as well as to decrease electrical consumption. Rather than refilling each humidifier upwards of four times a day for a month, the misting system required only occasional inspection and minimal electrical power. Additionally, if moisture dispersion is interrupted and the concrete dries during the 21-day moist curing cycle, the maximum strength of the concrete may not be achieved even if moisture is resupplied (*Neville*, 2010).

Backfire was placed in early February. Placement began bow-to-stern with a 3/16 inch first layer. Wooden depth checkers were used to maintain a uniform thickness throughout each concrete layer. In between first and second layers, fiberglass mesh was placed along the length of the hull with a 4 inch overlap for each piece. Carbon fiber scrim was placed on top of the fiberglass mesh, with a 1/16 inch concrete layer between the two, along the spine of the canoe as well as below paddlers in the bow and stern to resist punching shear and flexure in these zones.

Each rib received a carbon fiber strip insert, while gunwales received two strips of carbon fiber and a galvanized steel cable (3/64-inch diameter), creating a skeletal reinforcement structure for *Backfire*. Finally, a second 1/4 inch layer of concrete was placed in a manner similar to the first layer and then hand troweled, bringing the hull thickness to 1/2 inch as shown in Figure 14. This provided a buffer to account for outer hull surface irregularities that were sanded down to the average hull thickness of 3/8 inch.

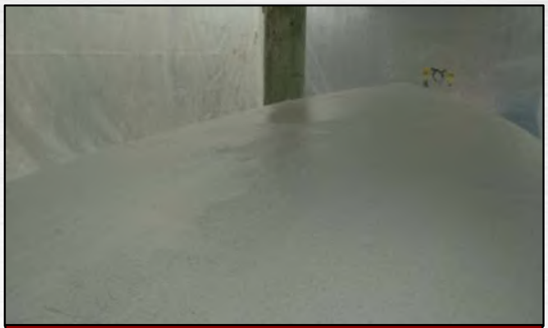


Figure 14. Trowel Finish of *Backfire*

After allowing concrete to set for three days in a humidified environment, the humidifiers were removed, the canoe was covered with permeable fabric, and the intermittent misting system was switched on as shown in Figure 15. This environment was held constant until the 7th day of curing when it was temporarily halted for wet sanding to begin on the outer hull. *Backfire* was kept in the hydration tent under these wet conditions for 21 days, at which point the tent was removed, allowing *Backfire* and all quality control test samples to air dry until day 28.

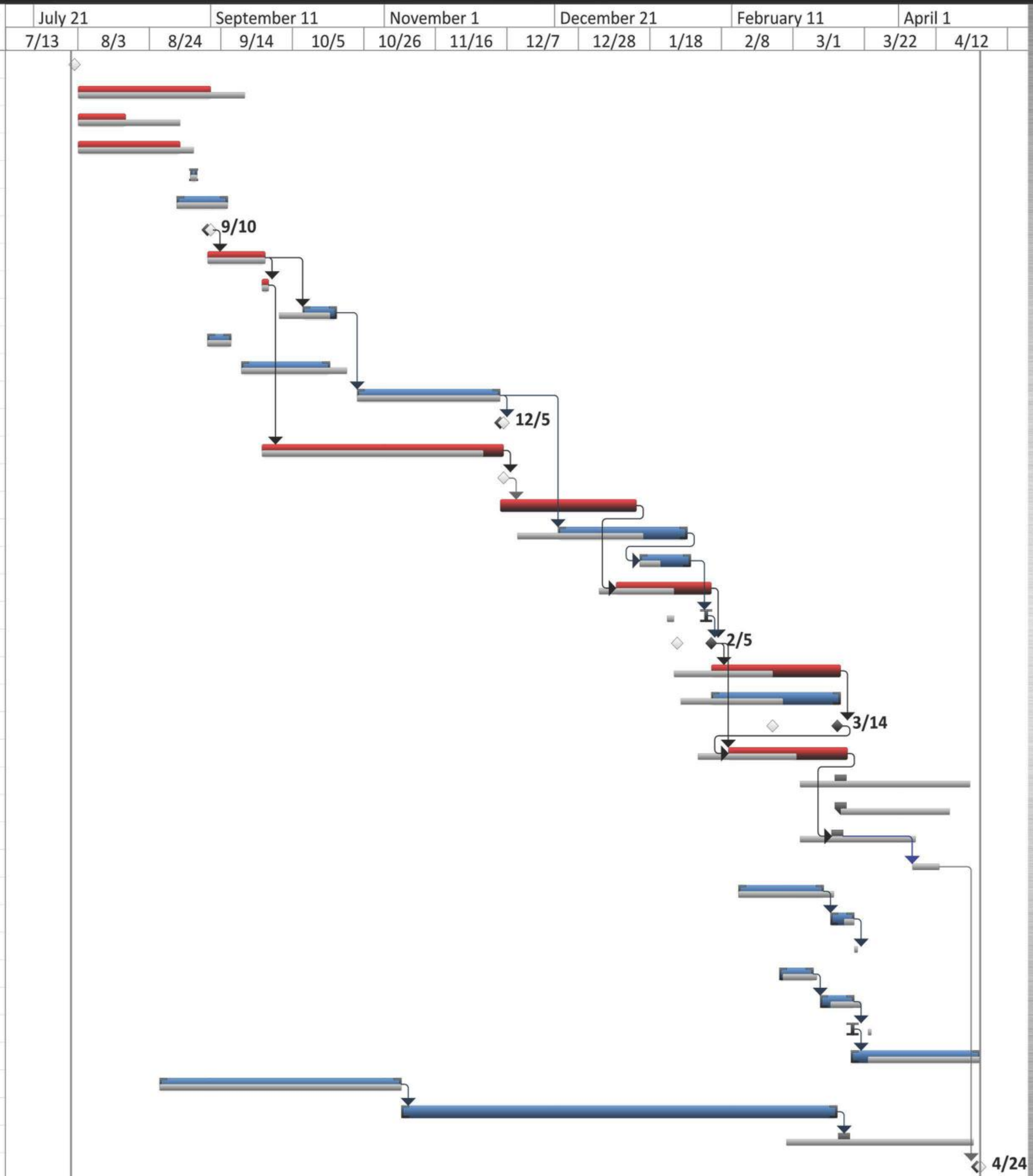
Figure 15. Intermittent Misting System

Starting with 60-grit sandpaper, *Backfire*'s construction team was able to wet sand the outer hull up to 500-grit by day 21. With Lowell's refined shadow sanding techniques, all imperfections on the outer hull were found and sanded. Once the exterior was shaped, the mold was unscrewed from the table. The cooling system was flushed, saving the glycol for next year, and the canoe was flipped onto stands. The mold was carefully removed one section at a time, beginning at mid-span and working towards each bulkhead. Sections will be re-used as part of the sectional with remaining pieces saved for UMass Lowell's 2016 season.

Excess joint compound on the inner hull was removed and light patching was performed. Sanding will advance up to 800-grit on the interior and 1500-grit on the exterior of the canoe. After sanding, the aesthetics team will take their blank canvas and transform it into *Backfire*. Graphics will be applied using image projection and freehand pencil outlines followed by the application of two layers of water-based stain. Vinyl lettering is to be adhered at the bow and stern prior to the application of two layers of sealer that will be wet sanded up to 2500-grit sandpaper, resulting in a smooth finish.

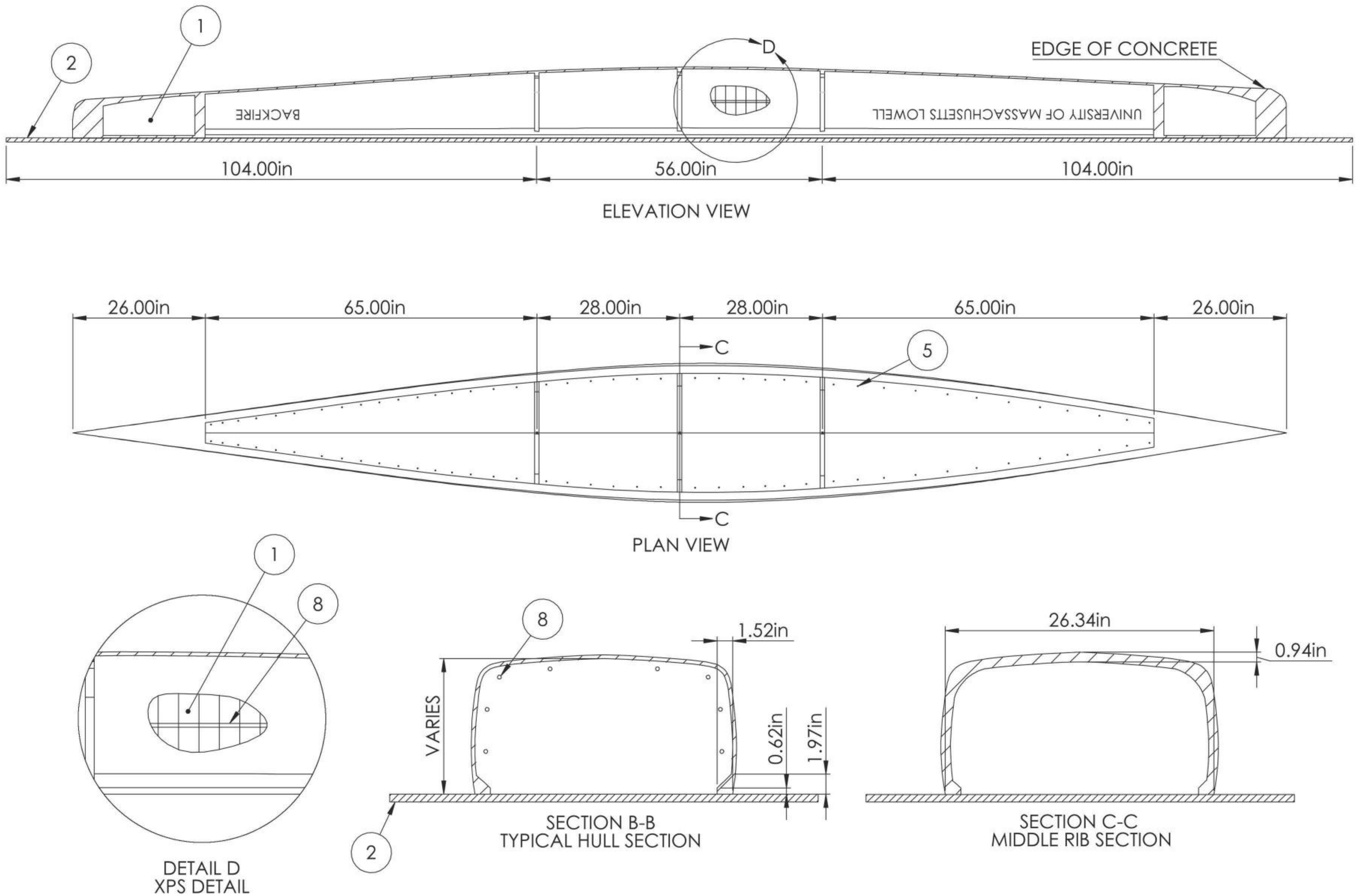
Many precautions were taken to ensure a safe work environment throughout the process. Workspaces were kept clean and clear of all hazards and MSDS were reviewed before the use of all materials. Rooms were properly ventilated and PPE was worn at all times. An overseeing Field Manager and Safety Officer instructed and ensured proper usage of all laboratory equipment. This supervision created a better final product and served as an opportunity to impart techniques from veteran members to Lowell's future team.

ID	Task Name	Planned Start	Planned Finish	Start	Finish	Duration
1	2014-2015 Project Planning Meeting	Fri 8/1/14	Fri 8/1/14	Fri 8/1/14	Fri 8/1/14	0 days
2	Mix Design Material Research	Sun 8/3/14	Sat 9/20/14	Sun 8/3/14	Wed 9/10/14	29 days
3	Cooling System Re-Design	Sun 8/3/14	Mon 9/1/14	Sun 8/3/14	Sat 8/16/14	12 days
4	Hull Design Research and Evaluation of Vanguard	Sun 8/3/14	Fri 9/5/14	Sun 8/3/14	Mon 9/1/14	22 days
5	Safety Inspection of Laboratory Facilities	Fri 9/5/14	Sat 9/6/14	Fri 9/5/14	Sat 9/6/14	2 days
6	Theme Development	Mon 9/1/14	Mon 9/15/14	Mon 9/1/14	Mon 9/15/14	11 days
7	Rules Released	Wed 9/10/14	Wed 9/10/14	Wed 9/10/14	Wed 9/10/14	0 days
8	Hull Design in ProLines7	Wed 9/10/14	Fri 9/26/14	Wed 9/10/14	Fri 9/26/14	13 days
9	Template Cutting for Mold Construction	Fri 9/26/14	Sat 9/27/14	Fri 9/26/14	Sat 9/27/14	2 days
10	Structural Analysis	Wed 10/1/14	Wed 10/15/14	Wed 10/8/14	Fri 10/17/14	8 days
11	Mix and Construction Material Procurement	Wed 9/10/14	Tue 9/16/14	Wed 9/10/14	Tue 9/16/14	5 days
12	Mix Design Preliminary Testing	Sat 9/20/14	Mon 10/20/14	Sat 9/20/14	Wed 10/15/14	19 days
13	Mix Design Finalist Re-Evaluation	Fri 10/24/14	Thu 12/4/14	Fri 10/24/14	Thu 12/4/14	30 days
14	Lead Sled Mix Selected	Fri 12/5/14	Fri 12/5/14	Fri 12/5/14	Fri 12/5/14	0 days
15	Lead Sled Mold Construction	Fri 9/26/14	Sat 11/29/14	Fri 9/26/14	Fri 12/5/14	51 days
16	Lead Sled Placement Day	Fri 12/5/14	Fri 12/5/14	Fri 12/5/14	Fri 12/5/14	0 days
17	Lead Sled Curing and Sanding	Fri 12/5/14	Mon 1/13/14	Fri 12/5/14	Tue 1/13/15	28 days
18	Mix Design Fine-Tuning	Wed 12/10/14	Thu 1/15/15	Mon 12/22/14	Wed 1/28/15	28 days
19	Backfire Mix Selected	Thu 1/15/15	Tue 1/20/15	Thu 1/15/15	Thu 1/29/15	11 days
20	Backfire Mold Construction	Sat 1/3/15	Sat 1/24/15	Thu 1/8/15	Wed 2/4/15	20 days
21	Placement Day Pre-Batching	Fri 1/23/15	Sat 1/24/15	Tue 2/3/15	Tue 2/3/15	1 day
22	Backfire Placement Day	Sun 1/25/15	Sun 1/25/15	Thu 2/5/15	Thu 2/5/15	0 days
23	Backfire Curing	Sun 1/25/15	Sun 2/22/15	Thu 2/5/15	Sat 3/14/15	28 days
24	Display Construction	Tue 1/27/15	Wed 2/25/15	Thu 2/5/15	Sat 3/14/15	28 days
25	Backfire Mold Removal	Sun 2/22/15	Sun 2/22/15	Sat 3/14/15	Sat 3/14/15	0 days
26	Backfire Sanding	Sun 2/1/15	Sun 3/1/15	Tue 2/10/15	Mon 3/16/15	25 days
27	Sectional Construction	Tue 3/3/15	Tue 4/21/15	Sun 3/15/15	NA	NA
28	Stand Construction	Sun 3/15/15	Wed 4/15/15	Sun 3/15/15	NA	NA
29	Canoe Aesthetics	Tue 3/3/15	Sun 4/5/15	Sat 3/14/15	NA	NA
30	Canoe Sealing and Sanding	Sun 4/5/15	Sun 4/12/15	NA	NA	NA
31	Design Paper Rough Drafts	Fri 2/13/15	Thu 3/12/15	Fri 2/13/15	Mon 3/9/15	17 days
32	Design Paper Editing	Mon 3/16/15	Wed 3/18/15	Thu 3/12/15	Wed 3/18/15	5 days
33	Design Paper Mailed for Submission	Thu 3/19/15	Thu 3/19/15	Thu 3/19/15	Thu 3/19/15	1 day
34	Presentation Script Development	Thu 2/26/15	Sat 3/7/15	Wed 2/25/15	Fri 3/6/15	8 days
35	Presentation PowerPoint Design	Thu 3/12/15	Fri 3/20/15	Mon 3/9/15	Wed 3/18/15	8 days
36	Presentation Peer Critique	Mon 3/23/15	Mon 3/23/15	Wed 3/18/15	Wed 3/18/15	1 day
37	Presentation Practice	Mon 3/23/15	Fri 4/24/15	Wed 3/18/15	Fri 4/24/15	28 days
38	Fall Paddling Try-Outs/Practice	Wed 8/27/14	Wed 11/5/14	Wed 8/27/14	Wed 11/5/14	51 days
39	Off-Season Conditioning	Fri 11/6/15	Tue 2/25/14	Thu 11/6/14	Fri 3/13/15	92 days
40	Spring Paddling Practice	Fri 2/27/15	Wed 4/22/15	Mon 3/16/15	NA	NA
41	New England Regional Competition	Fri 4/24/15	Fri 4/24/15	Fri 4/24/15	Fri 4/24/15	0 days



Project Schedule

Actual Milestone ◆ | Actual Execution | Start-only | Critical Path | Planned Execution | Planned Milestone ◇



University of Massachusetts Lowell

Bill of Materials		
No.	Qty.	Description
1	6-Piece	4' x 8' x 2" XPS Foam
2	3 Sheets	3/4" Plywood
3	1 Sheet	1/4" Plywood
4	1 lbs.	3" Deck Screws
5	1 lbs.	1" Deck Screws
6	4 Cans	Polystyrene Agent
7	2 Cans	Release Agent
8	300 Ft.	3/8" Vinyl Tubing
9	5	1/4" Brass Barb Splice
10	10	#4 Pipe Clamp
11	1 qt.	Water-based Polyurethane
12	4 lbs.	Joint Compound

Backfire
Form Design Drawing

General Notes:

1. Drawings not to scale
2. Construction adhesive applied to one side of each foam piece
3. Some screws omitted for clarity
4. Plywood base is one sheet thick
5. Plywood to extend 1" beyond final concrete surface

Engineer	Nicholas Brisbois
Drawn	Nicholas Brisbois
Checked	Jonathan Nadeau
Date	3/11/2015
	Sheet 11

Appendix A - References

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36. Utah State University Concrete Canoe Team. (2014). "*Promontory*." NCCC Design Paper, Logan, UT.

Appendix B - Mixture Proportions

				Design Proportions (Non SSD)		Actual Batched Proportions		Yielded Proportions	
Mixture ID: BACKFIRE STRUCTURAL									
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	533.49	2.714	3.42	0.017	480.96	2.447
CM2	White Silica Fume		2.20	14.33	0.104	0.09	0.001	12.92	0.094
CM3	Metakaolin		2.60	107.26	0.661	0.69	0.004	96.70	0.596
	Total Cementitious Materials:			655.09	3.48	4.20	0.022	590.58	3.14
Fibers									
F1	PVA		1.30	31.61	0.390	0.20	0.002	28.50	0.351
	Total Fibers:			31.61	0.39	0.20	0.002	28.50	0.35
Aggregates									
A1	3M™ K15	Abs: 0 %	0.15	86.74	9.267	0.56	0.059	78.20	8.355
A2	3M™ S38HS	Abs: 0 %	0.38	48.24	2.034	0.31	0.013	43.49	1.834
	Total Aggregates:			134.98	11.30	0.86	0.072	121.69	10.19
Water									
W1	Water for CM Hydration (W1a + W1b)		1.00	485.14	7.775	3.11	0.050	437.37	7.009
	W1a. Water from Admixtures			485.14		3.11		437.37	
	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)* **:**			485.14	7.77	3.11	0.050	437.37	7.01
Solids Content of Latex Admixtures and Dyes									
S1	Latex (if used)		1.00	93.58	1.500	0.14	0.002	84.36	1.352
	Total Solids of Admixtures:			93.58	1.50	0.14	0.002	84.36	1.35
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%	995.89	466.95	9.96	2.99	897.8	420.97
Ad2	ADVA Cast 575®	*8.9 lb/gal*	40%	16.91	7.67	0.17	0.05	15.2	6.92
Ad3	Eclipse® Floor 200	*7.9 lb/gal*	1%	26.02	10.52	0.26	0.07	23.5	9.48
	Water from Admixtures *(W1a)* **:**				485.14		3.11		437.37
	Cement-Cementitious Materials Ratio			0.814		0.814		0.814	
	Water-Cementitious Materials Ratio			0.65		0.65		0.65	
	Slump, Slump Flow, *in*.			2.00		2.00		2.00	
M	Mass of Concrete. *lbs*			1400.40		8.52		1262.51	
V	Absolute Volume of Concrete, ft^3			24.45		0.15		22.04	
T	Theorectical Density, lb/ft^3 = (M/V)			57.29		57.04		57.29	
D	Design Density, lb/ft^3 = $(M/27)$			51.87					
D	Measured Density, lb/ft^3					44.38		44.379	
A	Air Content, % = $[(T - D) / T \times 100\%]$			9.46		22.19		22.53	
Y	Yield, ft^3 = (M/D)			**27**		0.1919		**27**	
Ry	Relative Yield = (Y/Y_D)					1.109			

Appendix C - Bill of Materials

Material	Quantity	Unit Cost	Total Price
Cementitious Material			
White Portland Cement, Type I	79.04 lbs	$0.30	$23.71
Silica Fume	2.12 lbs	$1.11	$2.35
Metakaolin	15.89 lbs	$0.75	$11.92
Aggregates			
K-15	12.85 lbs	$12.50	$160.63
S38HS	7.15 lbs	$6.87	$49.12
Fibers			
PVA Fibers	4.7 lbs	$10.00	$47.00
Admixtures			
SilPro C-21 Latex	7.59 gal	$18.00	$136.62
Eclipse Floor 200	16.53 fl oz	$0.08	$1.32
ADVA Cast 575	25.43 fl oz	$0.09	$2.29
Reinforcement			
Fiberglass Mesh	75 sq ft	$0.04	$3.00
Carbon Fiber Mesh	20 sq ft	$0.03	$0.60
Galvanized Steel Cable	1 lump sum	$33.64	$33.64
Construction Mold			
Plotting Paper (42"x100')	1 roll	$80.00	$80.00
XPS Foam (4'x8'x2")	6 sheets	$30.00	$180.00
Plywood (various sizes)	1 lump sum	$125.00	$125.00
Deck Screws (various sizes)	1 lump sum	$16.94	$16.94
Vinyl Tubing (3/8")	300 feet	$0.24	$72.00
Brass Barb Splice (1/4")	5 units	$1.23	$6.13
#4 Pipe Clamp	10 units	$0.59	$5.87
Joint Compound	4 lbs	$0.58	$2.32
Polystyrene Spray Adhesive	4 cans	$6.35	$25.40
Release Agent	2 cans	$25.00	$50.00
Total Mold Construction Cost	1 lump sum	$563.66	$563.66
Finish			
Water-Based Stain	15 qts	$11.00	$165.00
Sealer	1 gal	$25.00	$25.00
Sanding Paper (various grits)	1 lump sum	$500.00	$500.00
Vinyl Lettering	1 lump sum	$200.00	$200.00
		Total Cost	$1,925.86
		Donated	$727.47
		Actual Cost	**$1,198.39**

Appendix D - Example Structural Calculation

Assumptions:

-Canoe is modeled as a simply supported beam (See free body diagram below).
-Paddler loads have been assumed as point loads.
-Dead load is considered to be uniform across the length of the canoe.
-Bouyant load is considered to be a triangular distribution (as opposed to volume) to provide conservative results.

Canoe Properties:

Overall Length: $L := 238\ in$ Length Between Paddlers: $L_b := 155\ in$ Assumed Canoe Weight: $W := 130\ lb$

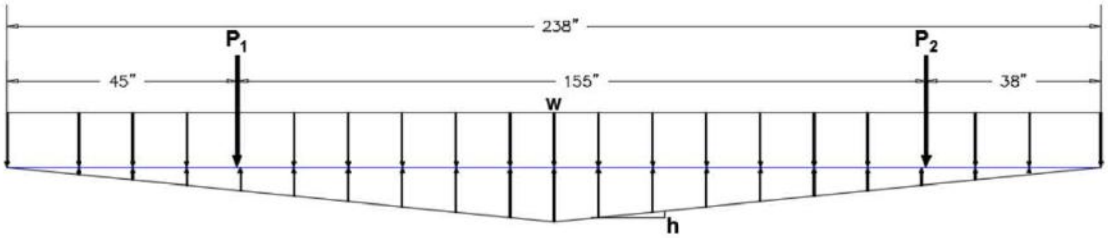
Paddler Information:

Paddler Weights: $P_1 := 165\ lb$ $P_2 := 185\ lb$

Paddler Locations: $x_1 := 45\ in$ (Aft of bow) $x_4 := 200\ in$ (Aft of bow)

Assumed Uniform Weight: $w := \frac{2 \cdot (P_1 + P_2)}{L} = 2.941\ \frac{lb}{in}$ Slope of Loading: $h := \frac{2 \cdot w}{L} = 0.025\ \frac{lb}{in^2}$

Buoyant Force: $F_b := P_1 + P_2 + W = 480\ lb$



Determination of Critical Shear, V(x) and Critical Moment M(x):

Note: The following shear and moment calculations have been simplified to illustrate proper understanding of a two-dimensional classical analysis for this sample structural calculation.

$x_0 := 0\ in$ $V_0 := \frac{h}{2} \cdot x_0^2 = 0\ lb$ $M_0 := \frac{1}{2} \cdot V_0 \cdot x_0 = 0\ lb \cdot in$

$x_1 := 45\ in$ $V_1 := \frac{h}{2} \cdot x_1^2 = 25.025\ lb$ $M_1 := M_0 + \frac{1}{2} \cdot V_1 \cdot x_1 = 563.056\ lb \cdot in$

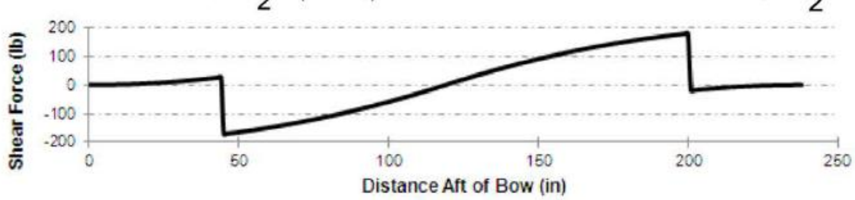
$x_2 := 45.1\ in$ $V_2 := \frac{h}{2} \cdot x_2^2 - P_1 = -139.864\ lb$ $M_2 := M_1 + \frac{1}{2} \cdot V_2 \cdot x_2 = -2590.876\ lb \cdot in$

$x_3 := 115.5\ in$ $V_3 := \frac{h}{2} \cdot x_3^2 - P_1 = 0\ lb$ $M_3 := M_2 + \frac{1}{2} \cdot V_2 \cdot (x_3 - x_2) = -7514.086\ lb \cdot in$

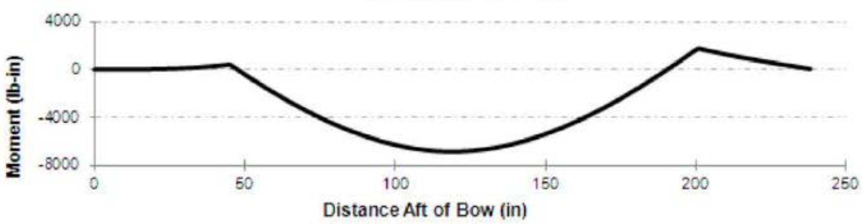
$x_4 := 200\ in$ $V_4 := P_1 - \frac{h}{2} \cdot (L - x_4)^2 = 147.155\ lb$ $M_4 := M_3 + \frac{1}{2} \cdot V_4 \cdot (x_4 - x_3) = -1296.779\ lb \cdot in$

$x_5 := 200.1\ in$ $V_5 := P_1 - \frac{h}{2} \cdot (L - x_5)^2 - P_2 = -37.751\ lb$ $M_5 := M_4 - \frac{1}{2} \cdot V_5 \cdot x_5 = 2480.208\ lb \cdot in$

$x_6 := 238\ in$ $V_6 := \frac{h}{2} \cdot (L - x_6)^2 = 0\ lb$ $M_6 := \frac{1}{2} \cdot V_6 \cdot x_6 = 0\ lb \cdot in$



$V_{max} := V_4 = 147.2\ lb$

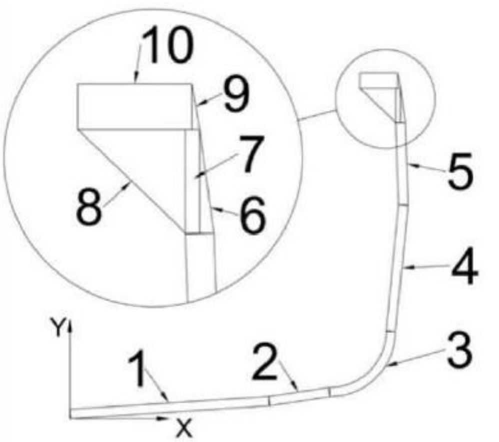


$M_{max} := M_3 = -7514.1\ lb \cdot in$

$M_{max} := -M_3 = 7514.1\ lb \cdot in$ (Magnitude)

Determination of Moment of Inertia for Critical Section:

Note: Moment of Inertia values were obtained by transforming the cross section into simple geometric shapes and using the following formulas with the help of hand-drafting tools for calculation:



Piece	Area (in²)	ȳ (in)	Aȳ (in³)	I_x (in⁴)
1	2.99	0.45	1.34	0.70
2	0.91	0.89	0.81	0.74
3	1.44	1.96	2.82	6.35
4	1.91	6.07	11.59	74.40
5	1.26	10.27	12.94	134.10
6	0.04	12.39	0.55	19.90
7	0.13	12.62	1.63	42.28
8	1.00	12.86	12.85	165.34
9	0.03	13.53	0.45	6.10
10	0.94	13.63	12.81	173.90

Half Moment of Inertia about X Axis: 623.81 in^4

Total Moment of Inertia about X Axis: 1247.61 in^4

*Calculation for Moment of Inertia (I_x) was completed by analyzing one half of the critical section and multiplying final result by 2.

$I_{xHalf} := \sum_{i=1}^{10} (I_x)$ $\quad I_{xHalf} := 623.81\ in^4$ $\quad Y := 5.42\ in$ $\quad c_c := -Y = -5.42\ in$

$I_x := 2 \cdot I_{xHalf}$ $\quad I_x = 1247.62\ in^4$ $\quad Height := 13.9\ in$ $\quad c_t := Height - Y = 8.48\ in$

Formulas for Pieces 1, 2, 4, 5, 7, 10: $A_{Rectangle} := b \cdot h$ $\quad I_{xRectangle} := \frac{1}{12} \cdot b \cdot h^3$

Formulas for Pieces 6, 8, 9: $A_{Triangle} := \frac{(b \cdot h)}{2}$ $\quad I_{xTriangle} := \frac{1}{12} \cdot b \cdot h^3$

Formulas for Piece 3: $A_{Annulus} := \frac{1}{4} \cdot \left(\pi \cdot r_o^2 - \pi \cdot r_i^2\right)$ $\quad I_{xAnnulus} := \frac{1}{16} \cdot \left(\pi \cdot r_o^2 - \pi \cdot r_i^2\right)$

Determination of Maximum Compressive and Tensile Stresses:

Dynamic Amplification Factor, DAF: $DAF := 1.25$ (*Paradis*, 2007)

Mix Design Safety Factor, MDF: $MDF := 2.5$ (Accounts for potential errors in mix design or construction)

Design Compressive Stress: $f_{cMax} := \frac{DAF \cdot MDF \cdot M_{max} \cdot c_c}{I_x} = -102\ \frac{lb}{in^2}$

Design Tensile Stress: $f_{tMax} := \frac{DAF \cdot MDF \cdot M_{max} \cdot c_t}{I_x} = 160\ \frac{lb}{in^2}$