THE MAROON MACHINE

Arizona State University

Tempe, AZ

2019 Concrete Canoe
Design Report

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Scooby-Doo's goofy ability to solve crime inspired this year's theme by providing a relatable experience for the meddling college students who created a canoe out of concrete. The canoe is named *The Maroon Machine* because Scooby-Doo always jumps in The Mystery Machine ready for an adventure, and this year's team is jumping in the boat, ready for victory.

Arizona State University is located in Tempe, Arizona and was founded in 1885. ASU has grown to be the largest public university in the United States with over 98,000 currently enrolled students ("Arizona State University"). The Ira A. Fulton Schools of Engineering within ASU currently enrolls almost 22,500 students with approximately 1,600 of those in the School of Sustainable Engineering and the Built Environment as civil, environmental, and sustainable or construction engineering and construction management majors (Ira A Fulton, School of Sustainable Engineering and the Built Environment).

The ASU Concrete Canoe team competes in the Pacific Southwest Conference and placed third with *Pondicherry* (2016), ninth with *Firebolt* (2017), and seventh with *Bullet Bill* (2018). The 2019 team hopes to improve through this year's fresh leadership, improved task delegation, increased funding, alumni support, and innovations in hull design, construction, and the curing process.

Due to the departure of the team's experienced leadership, this year's team was composed primarily of first time members with three previous members taking on the major roles. This allowed the team to look at the task with fresh eyes, implement better and more frequent communication modes, and allocate earlier deadlines to allow for a margin of error.

With the help of alumni, a MATLAB code was written to perform structural calculations instantaneously to drastically speed up the hull design and analysis. This made construction cheaper and more sustainable by outputting AutoCad files for a student-used milling machine that optimized the number of cross sections per piece of foam used. The hull design team incorporated ribs into the canoe design to help the paddlers maintain their stability and mesh into the gunnels to reinforce a key area of failure. Table 1 details pertinent properties of the canoe.

Table 1. Canoe Physical Properties

Property	Value
Name	The Maroon Machine
Length	240 in
Width	28 in
Depth	14 in
Average Thickness	0.75 in
Estimated Weight	230 lbs
Colors	Gray, Red, Yellow, Black
Primary Reinforcement	Fiberglass Mesh
Secondary Reinforcement	Glass Fibers

Table 2. Mix Design Properties

Mix Type	Gray Structural	Red Structural
Wet Density	62.81 pcf	64.99 pcf
Dry Density	61.39 pcf	60.02 pcf
Compressive Strength[1]	1800.9 psi	1307.6 psi
Tensile Strength[2]	520.2 psi	377.7 psi
Composite Flexural Strength[2]	1662.4 psi	1207 psi
Air Content	8.30%	5.10%
[1]28-day, [2]14-day		

The mix design team promoted sustainability techniques by incorporating recycled materials such as Class F Fly Ash, VCAS, and recycled glass Poraver. In addition, the final mix design for *The Maroon Machine* used a reduced amount of Ordinary Portland Cement and replaced it with more sustainable cementitious materials, resulting in reduced CO_2 emissions associated with the life cycle of cementitious material.

The construction team improved the process by changing the semi-permanent curing chamber to be autonomous, segmented, and permanent for this and future canoes. This curing chamber ran a misting system automatically, drained water out of the chamber autonomously, and allowed for parts of the chamber to be opened individually so the canoe could be checked without harming the integrity of the curing conditions. The construction team also improved upon the aesthetics of the canoe by incorporating pigmented concrete, inlays, and themed designs on the body of the canoe. The ASU team is excited to present *The Maroon Machine*: a heartfelt tribute to the universal experience of a group of friends and their dog solving problems, going on adventures, and having fun all the while.

Hull Design and Structural Analysis

Hull Design

The hull design team's primary goal was to reduce cracking that propagated from the gunnel. Gunnel and hull cracking became a serious issue as the previous year's canoe *Bullet Bill* is currently out of service and close to more severe fractures. Design and analysis began by using the program developed in MATLAB ("MathWorks R2018b") that designed the shape of the hull using Scaling and Splining, a method developed by former Project Manager Steven Sherant. The hull design program takes inputs for the location of the bow, stern, and widest/deepest point to develop plan end elevation views of the hull. Three points are used for each input, and fitted using quadratic splines. After creating the primary design, the cross-section is shaped at the deepest point using intermediate points connecting the gunnel to the keel. These points shape the walls, chine, and bottom of the cross section. All points are fitted using quadratic splines, and then offset to create the inner and outer surfaces. The key input points are shown as black dots, and the splines are the blue and green lines.

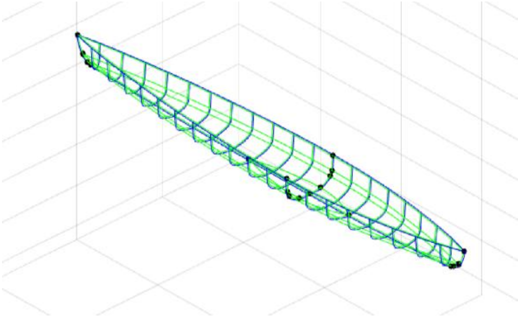


Figure 1. MATLAB Quadratic Spline Output

Bullet Bill's hull design was used as the baseline for *The Maroon Machine's* design. The hull profile was kept the same as a mixture of a flat and round bottom, giving the canoe fast straight-line speed, while still providing enough maneuverability to navigate the course. The sides of the hull above the chine remained straight, with a slight flare outward to provide ease of paddling, and a slight advantage to secondary stability. The gunnel rails were kept constant with 2" diameter rails, to reduce cracking originating from tension in the gunnels. The bow and stern rocker were kept at 4", to ensure advanced maneuverability and primary stability during sprints.

Another key assessment was the design of the rocker. With the rocker set at 4", deadlift (the depth the bow or stern is submerged) is reduced. Reducing deadlift decreases displaced water and wetted surface area, providing a smaller wake off the bow and stern of the canoe. Consequently, increasing the rocker will decrease tracking. To compensate, the widest point of the hull was kept at 1' aft of midship. This creates a longer, streamlined bow, which allows the canoe to recoup tracking ability, and travel faster due to a sharper entry line.

To address primary stability, the hull profile was fitted with a soft chine. This profile was chosen because it will decrease turbulence along the bottom of the hull and allows for smoother transitions into turns. Soft chines tend to have slightly less wetted surface area, decreasing drag resistance due to water. Although, having a soft chine also allows for a wider hull at higher waterlines, which increases beam length vertically along the cross-section. Though this increases stability, it decreases the L/B ratio which should be maximized to produce a hull much longer than it is wide, similar to an arrow, but there had to be middle ground found between stability and efficiency.

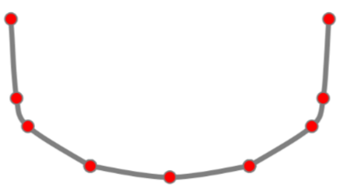


Figure 2. Hull Profile with spline node inputs

The beam length increases from the end of the chine to the start of the gunnel. As the boat sits lower in the water, this allows the length of the waterline to increase, providing an increase in speed, since length of the waterline is related to speed of the hull. This design will allow the transverse metacentric height (GM_T) to remain at 1.10, a value that provided a good compromise between overturning resistance and primary stability on *Bullet Bill*.

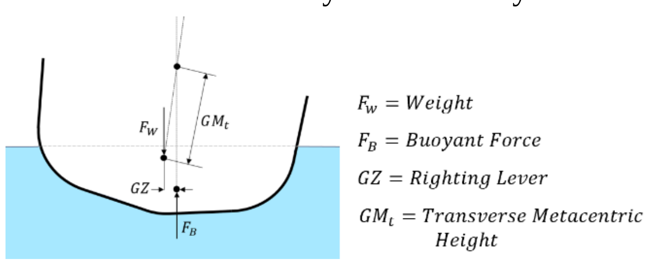


Figure 3. Righting Lever and GM_T

The Maroon Machine's final hull design is asymmetric with a shallow arc bottom on the ends, a flat bottom in the center, and slightly flared walls. The overall length is 20', and at the widest section, beam width is 28" and depth is 15". The bow and stern both have depths of 16", while the thickness of the boat is ¾" throughout.

Structural Analysis

Upon completing the hull design, the team performed a two-dimensional longitudinal and lateral analysis to ensure *The Maroon Machine* would endure all loading conditions. MATLAB was used in combination with Excel to compute cross-sectional properties and perform each analysis. Five loading cases were taken into account: (1) display, (2) carrying, (3) two female paddlers, (4) two male paddlers, and (5) coed.

To complete the longitudinal analysis, the canoe was modeled as a simply supported beam with self weight and paddler weight acting in the negative gravity direction and buoyant force acting in the positive gravity direction. Cuts were taken at 1" intervals to compute the internal forces and moments acting on the cross section.

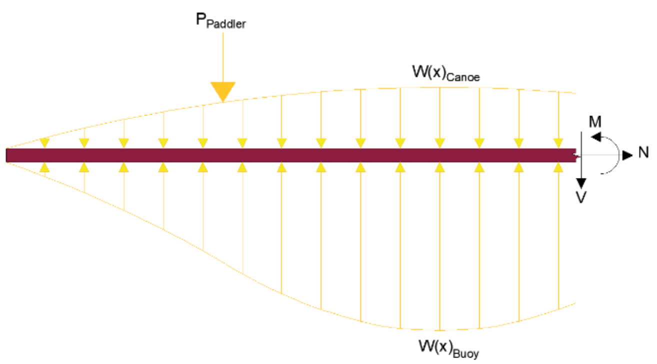


Figure 4. Free Body Diagram for longitudinal analysis

Unit weight of concrete was estimated at 60 pcf, a conservative estimate resulting in a total weight of 250 lbs. The paddlers were modeled as 190 lbs point loads for males, and 130 lbs for females. To analyze paddling load cases, the net downward forces were set equal to the resultant of the upward buoyant force, allowing for the canoe to remain in static equilibrium and the elimination of simple support reactions. The resultants of the net downward and upward forces were aligned at the centroid of the canoe, to eliminate any residual moments. Bending stresses were determined using the theory of simple bending: $\sigma = Mc/I_x$, where: M is the bending moment, c is the distance from the neutral axis to the outer most fiber, and I is the section modulus. The bending stresses were computed using MATLAB. On-land load cases were analyzed as a simply supported beam. Bending moment diagrams were created for each load case. A dynamic load amplification factor of 2 was applied to account for momentum generated by paddlers.

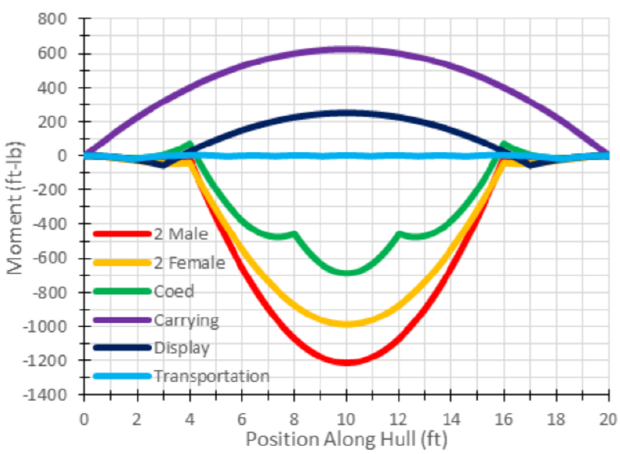


Figure 5. Bending moment envelope

A new design implemented was a layer of mesh reinforcement inside the gunnel rail. *Bullet Bill* developed cracking in the gunnel in multiple locations that propagated deep into the sidewalls. The mesh used was 2" wide and was designed to be placed uniformly throughout the gunnel. The additional mesh will mitigate cracks that develop in the gunnel through paddling, carrying, and transportation. Also, incorporated in the new design were 4 - 1" diameter ribs, to provide stability to paddlers during competition. The ribs will allow paddlers to brace themselves, and slightly increase rigidity in the hull.

Table 3. Maximum Theoretical Structural Stresses

Load Case	Compressive (psi)	Tensile (psi)
2 Male	160	155
2 Female	127	123
Coed	231	224
Carrying	131	110
Display	16	31

The overarching goal for the 2018-2019 mix design team was to generate a concrete mix that was strong enough for racing using new materials. Previous years dealt with balancing buoyancy and weight for ease of paddling, and the team wanted to continue with this good balance. Additionally, funding issues in the first semester prevented the team form ordering the same admixtures as last year, thus different ones were donated. Using last year's mix design as a baseline, the design team set out to make a mix that would be both stable and strong using these new admixtures.

The mix design of *Bullet Bill* served as a baseline for *The Maroon Machine* due to its stability and strength. *Bullet Bill* consisted of Ordinary Portland Cement (OPC), Class F Fly Ash, Metakaolin, VCAS-8, Utelite Clay Shales with size variations, 3M Glass Bubbles, Poraver (0.1-2.0 mm), GRACE short glass fibers, Acryl-60 (latex), AEA-92 (air entrainer), and ADVA Cast 575 (high range water reducer). *Bullet Bill* possessed a dry unit weight of 60.50 pcf, a 28-day compressive strength of 1914.6 psi, and a tensile strength of 588 psi. Focus was placed on utilizing the new admixtures to generate a comparable or superior strength mix without compromising the stability in order to aid paddlers.

The design process began by formulating a plan with numerous options on how to incorporate the new admixtures and maintain the strength of the concrete and the canoe's stability in the water. The three admixtures added to the mix were Plastol 6400 (high range water reducer), AEA-92 (air entrainer), and Acryl 60 (latex). The first option was to continue using latex and lower the amount of latex and water reducer to achieve the desired consistency, strength, and weight. This was evaluated by proportionally decreasing the amount of each admixture while maintaining the amount of each aggregate type and cementitious material that was used in the mix. This ensured that the gradation of *Bullet Bill's* mix was left intact, and that the sole effect of the admixtures could be examined.

Table 4. Admixtures

Admixture	Type	Recommended Dosage	Structural Mix
AEA-92	AEA	0.1-7 fl oz/cwt.	9 fl oz/cwt.
Plastol 6400 575	HRWR	3-12 fl oz/cwt.	2.5 fl oz/cwt.
ACRYL 60	Latex	-	0 fl oz/cwt.

Initial mix designs were conducted with decreases in water reducer and latex in increments of 1ml. After testing these mix designs for their compressive strength, it was clear that these admixtures were negatively affecting the strength as the designs ranged in compressive strength from 550-850 psi. In addition to the great decrease in strength from the previous year, the mixes were too fluid to be placed on the canoe mold. The weight, however, was consistent with the previous year's mix design (close to 60 pcf) for the variety of mixes tested. As a result, latex was eliminated from the design and water reducer was tested in 0.5 ml increments with 2.5 ml of water reducer resulting in a desirable consistency and a compressive strength of 1510.56 psi (slightly lower than the previous year's compressive strength). From the results, changing the initial proportions of latex and water reducer was not a good approach as the poor consistency of them combined compromised the strength, but the elimination of latex in further testing, along with optimizing the water reducer resolved this issue. Overall, the addition of new admixtures without compromising strength was achieved through the mix design process and the final admixtures used in the mix are shown in Table 4.

Table 5. Properties of Aggregates

Aggregate		Specific Gravity	Adsorption (mass %)	Grain Size (Mesh #)
Poraver	0.1-0.3mm	0.9	70	140-50
	0.25-0.5mm	0.68	60	60-35
	0.5-1.0mm	0.47	50	35-18
	1-2mm	0.41	40	18-10
Clay Shale	Crushed Fine	0.845	18.9	4-pan
	Fine	0.854	17.8	4-pan
	10 Mesh	0.825	13.3	4-pan

As determined last year by the mix design team, *Bullet Bill*'s mix had a minimal amount of air voids and was devoid of an excess of grains, making casting simple without affecting the quality of the finish. The gradation of the mix for *The Maroon Machine* was taken from the gradation used for Bullet Bill. The initial gradation was performed digitally rather than through trial mixes, thus reducing person-hours and material waste.

This theoretical approach was executed by creating a 0.45 power chart in Excel which was used to analyze a wide distribution of possible volume fractions. The gradation from Bullet Bill was tested as the trial mix using 12.82% of Fine Clay Shale, 8.97% Crushed Fine Clay Shale, 3.85% 10 Mesh Clay Shale, 16.67% 3M Glass Bubbles, 10.26% Poraver (0.1-0.3), 5.13% Poraver (0.25-0.5), 30.76% Poraver (0.5- 1.0), and 11.54% Poraver (1.0-2.0) by volume with all relevant aggregate properties displayed in Table 5.

The four cementitious materials used were Ordinary Portland Cement (OPC), VCAS-160, Fly Ash Class F, and Metakaolin. The final weight distribution of these cementitious materials was found to be 49% OPC, 15% VCAS-8, 26% Fly Ash, and 10% Metakaolin. This distribution was the same as *Bullet Bill's* due to its continued excellent performance, as shown in Figure 6.

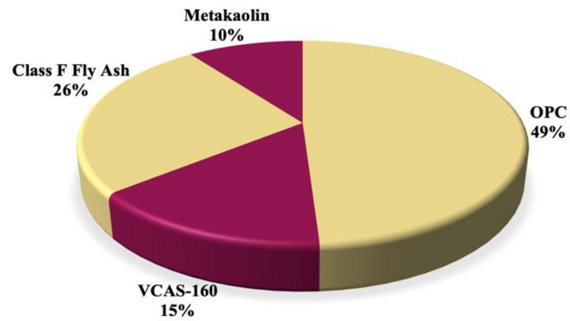


Figure 6. Cementitious Material Gradation

Implementing fiber reinforcement into the canoe was further examined to improve tensile strength because concrete is known to be weak in tension. The canoe has two types of reinforcement: the primary reinforcement withstands stress from structural loads such as the paddlers, while the secondary reinforcement bridges and resists possible fracturing and shrinkage.

For the primary reinforcement, this canoe had the same reinforcement as last year's canoe, *Bullet Bill*, which was a dual layer white fiberglass mesh. The white mesh was placed with fiber orientation in the principle directions to acquire an equal fiber distribution and to improve tensile and flexural strength. To successfully implement this mesh, the mix needed to have the correct amount of workability and adhesiveness to allow a secure impregnation. This was tested by creating 14 inch by 4 inch by 0.75 inch beams, which resulted in a 300% increase in flexural strength compared to a beam with no primary reinforcement. In addition, the white mesh is finer compared to other tested mesh, meaning it had a higher volume fraction of textile that provided more bridging to minimize crack propagation through the matrix. Furthermore, mesh was added alongside the gunnels of this year's canoe to improve this section's strength and minimize cracking.

For the secondary reinforcement, the mix design team continued to incorporate GRACE short glass fibers. These fibers were ideal for this mix because of their light weight, and optimizing, capabilities by better dispersing in the concrete due to their length. Longer plastic fibers were also tested in the mix for increased strength and reduced cost, but were excluded from the mix because of their poorer ability to disperse in the mix and their affinity for clumping. Thus, the original effective fiber distribution was able to minimize the fractures and allow the concrete to withstand higher stress values. Therefore, a similar fiber distribution and amount from *Bullet Bill's* mix design

Table 6. Summary of Materials

Material	Company	Usage	ASTM Standard
OPC	Federal White Cement	Cementitious Materials	C150
Metakaolin	Burgess Pigment		C618
Fly Ash Class F	SRMG		C441/C1012
VCAS	Burgess Pigment		C1157
Crushed Clay Shale	Utelite	Aggregates	C330
Fine Clay Shale	Utelite		C331
10 Mesh Clay Shale	Utelite		C330
Poraver (0.1-0.3mm)	Poraver		C136
Poraver (0.25-0.5mm)	Poraver		C136
Poraver (0.5-1.0mm)	Poraver		C136
Poraver (1.0-2.0mm)	Poraver		C136
Glass Bubbles	3M	Solids/ Admixtures	D281-84
AEA-92	Euclid		C260
ADVA Cast 575	GRACE		C494/C1017
Black Pigment	Davis Colors		C979-82
Red Pigment	Euclid		C979
Yellow Pigment	Euclid		C979
Microfibers	GRACE	Fibers	C1116

was desired, as the amount of fibers had been decreased the previous year due to them protruding along the surface of the canoe. The fibers were included in the cementitious portion of the mix, as opposed to being added as the last step in the mixing process, to ensure an even distribution and better dispersion, and to minimize clumping. All in all, the implementation of both reinforcements was successful in improving the tensile and flexural strength of concrete without compromising weight.

A red structural pigment mix was also designed alongside the standard gray mix to add aesthetic appeal to the canoe. The mix design was the same as the gray structural mix except for a higher dosage of water reducer (3 ml) to ensure a sufficient strength (1833.5 psi) and consistency for the 0.06 lb of added red pigment. Additional yellow and black pigmented mixes were also designed for use in the flower inlays but were not designed to be structural. Table 6 shows all the materials utilized in the mix.

Sustainability was a primary goal in selecting the types of materials used, therefore, the use of supplementary cementitious materials contributed greatly to the sustainability of the mix. OPC, although practical in its ability to resist cracking and shrinkage, is cost and energy-intensive to manufacture, and the calcination reaction used to manufacture it from limestone has carbon dioxide as a 1:1 stoichiometric product; thus, it’s usage was reduced. The reduction of OPC was substituted with an increase in the usage of Fly Ash; with this material, the advantages far outweigh the disadvantages. Fly Ash is a waste product of coal-burning power plants, and it is more environmentally friendly to use its low heat-of hydration pozzolanic reaction to bind concrete than it is to disperse it throughout the air or sequester it to landfills. Another benefit to using Fly Ash is its reduced permeability to water and harsh chemicals. Concrete that is properly cured with fly ash will be denser due to the material’s smaller pore size, thus resulting in increased strength. VCAS is manufactured from industrial by-products, so its use in concrete diverts waste from landfills and the increased durability it adds to concrete reduces the future need for repairs and replacements. The use of VCAS in a wet concrete mix results in a lower demand of water, improved workability, and ease of placement on the mold. Once the concrete hardens, VCAS ensures decreased permeability and increased strength and longevity. Metakaolin is produced by heat-treating the mineral kaolin, which is found in abundance in North America. Due to its high reactivity, small amounts of metakaolin in a concrete mix can produce great increases in compressive strength and durability. Furthermore, due to the ability to process this material at a lower temperature compared to other cementitious material, the use of metakaolin in concrete mixes is a more sustainable practice that works towards saving energy and reducing greenhouse gas emissions. To minimize the quantity of waste generated by the mix design process, the overall number and proportion of admixtures that were necessary for the mix design were reduced. Moreover, before any trial designs were mixed and cast, they were subject to peer review to ensure that each mix was logically designed and had a clear investigatory purpose. Before Cast Day, the number of batches of cementitious and aggregate materials needed was calculated and pre-batched. In past years during the pre-batching process, any extra material measured was put into a waste container. This year, the excess material was placed back into its original container; this process may have been more time consuming, but it resulted in zero wastage of material. Furthermore, all leftover batches of material from the pre-batching were saved and will be reused for next year’s mix design testing, much like how remaining pre-batches from the previous year were used by the team this year to train new mix design members.

Overall, the mix design team’s extensive research and testing led to a final mix that met the set goals. The final design utilized the new admixtures to maintain a satisfactory compressive and tensile strength compared to the canoe’s predecessors. This final mix led to the creation of *The Maroon Machine* with the design properties shown in Table 7.

Table 7. Final Testing Results

Property	Required	Gray Structural	Red Structural
Dry Density	<62.43 pcf	61.39 pcf	60.02 pcf
Compressive Strength[1]	231 psi	1800.9 psi	1307.6 psi
Tensile Strength[2]	224 psi	520.2 psi	377.7 psi
[1]28-day, [2]14-day			

Due to the failure modes and lack of aesthetics of previous years' canoes, the construction of this year's canoe was focused on secondary reinforcement, wet curing, and aesthetic design. A male mold was utilized because of the ease of adding ribs to the design without compromising the integrity of the mold or the construction process. The mold was made of 2 pcf expanded polystyrene (EPS) foam due to the additional buoyancy when left in the bulkheads and because of its easy constructability.

AutoCAD was used to draft the finalized hull design from outputs from a Matlab code where cross-section cuts were taken at two-inch intervals, generating a stair-step pattern when assembled. These cross sections were imported into VCarve Pro, a toolpathing software that converts AutoCAD cut files into readable CNC (Computer Numeric Control) machine files. The sustainability of the process was improved by using VCarve's optimization tool, thus maximizing the number of cross-sections per sheet of foam so that 6 less foam sheets were used and less foam waste was generated. The Innovation Hub at Arizona State University Polytechnic campus provided free access and training on the ShopBot CNC machine, resulting in a cost savings of $3000 towards the construction, as opposed to out-sourcing the milling.

The sections were then assembled, adhered, and fitted along a continuous steel bar using Glidden Gripper, an all-purpose paint primer and sealer that proved more durable and sturdy than the previous year's adhesives. Ribs placed at 5.5 feet, 9 feet, 11 feet, and 14.5 feet along the length of the canoe were carved out of the Styrofoam using a heavy duty hot knife and a portable fume hood was used to capture the toxic, volatile compounds released when Styrofoam is burned to promote sustainability. The mold was hand-sanded using 80-grit sand paper to create smooth transitions between adjacent sections. After mold sanding, Rosco Foamcoat™ was applied to the body, ribs, and gunnels (offset two feet from each end for the bulkheads) to provide a smoother finish to the mold, easier removal of the mold from the concrete, and a tougher protective layer between the Styrofoam and concrete. Each layer was sanded to minimize imperfections and the final layer was finished using an orbital sander. To improve upon the previous year, the Rosco Foamcoat™ was not watered down before application, each layer was smoothed out using hand tools before drying, and each layer was thicker. To improve upon the releasing agent performance from the previous year, more layers of Kleen Kote Releasing Agent were applied to the canoe in the days leading up to cast day for easier removal of the mold from the canoe (releasing agent was not applied to the bulkheads). A mix ratio of one part Kleen Kote 100 concentrate to eleven parts water was used for application as suggested by the manufacturer. This releasing agent promoted sustainability by being biodegradable, by having a low volatile organic compound (VOC) value of 15 g/L, and by being shipped as a concentrate as opposed to a mix that has eleven to fifteen times the volume. Figure 7 shows the finished canoe mold with the white Styrofoam stair-step in the bottom right corner, hand-carved ribs incremented along the body, sanded gray FoamCoat offset from the bulkheads, and clear releasing agent on top of the FoamCoat.

Figure 7. Finished canoe mold

The Maroon Machine incorporates two layers of fiberglass mesh to resist tensile forces, act as secondary reinforcement to the layers of concrete, and protect against puncture. The mesh was pre-measured and pre-cut to expedite its placement while casting. Due to the small width of the mesh, additional mesh reinforcing was cut to cover the reminder of the canoe and provide a two-inch overlap with the other sheet of mesh to ensure proper reinforcement. The Maroon Machine also contains 2.5" wide mesh placed along the vertical curvature of the gunnels to provide additional support in response to the fracture of last year's canoe whose cracks propagated in the unreinforced gunnels.

For curing, the team constructed an automated, sustainable curing chamber built off the previous curing chamber. A misting system was constructed by running a tube, with misters placed every 2.5 feet, along an existing PVC pipe system on the roof of the chamber that created a rectangle encompassing the canoe. The misting system was scheduled to run every 3 hours for 30 minutes, creating a controlled environment providing proper hydration and humidity for an efficient wet curing process to combat the dry Phoenix air. A shower curtain system of tarps was attached to the existing steel frame that allowed for easier access to check on the canoe during curing and for the excess water from the misting system to be caught and diverted to a gutter system along the edge of the cast table. These gutters directed the water to a large trough set to be pumped dry every 2.5 hours. This permanent, self-sustaining, and effective curing chamber is an improvement over last year's which required constant attention to fix leaks and to maintain moisture.

The canoe was cast in a ten-step process to resemble *The Mystery Machine*, using an ASU color scheme, and to implement previously mentioned changes (Figure 8). First, the gunnel rails were half-filled with a gray structural mix, then a thin strip of mesh was layered into the concrete, making sure to have some curvature to best protect the gunnel. The remainder of the gunnel and the ribs were then filled in with structural gray concrete until they were flush with the body of the mold. Next, gray structural concrete was placed over the whole of the mold extending ¼" from the main body of the canoe. Tire tread-depth gauges were used to ensure even thickness over the entire layer and hand tools were used to smooth out the concrete once it was placed. The bulkheads were hand-formed by experienced volunteers at both the bow and stern. Next, the main section of fiberglass mesh was placed over the body of the canoe, followed by the side panels, and all three pieces were smoothed into the layer of concrete to promote proper adhesion of the mesh and layers of concrete. A second layer of gray structural concrete was placed, followed by the second layer of fiberglass mesh. For the third layer of ¼" thick concrete, the color design changed so that the bottom of the canoe would be constructed using red pigmented structural concrete placed to look like the bottom of the Mystery Machine's side panel, while the top of the canoe would be filled in with more gray structural concrete. After the body was casted, the leadership team placed four yellow and black flower inlays to complete the design. The canoe was then wrapped in cheesecloth while curing to ensure the concrete remained moist.

Figure 8. Volunteers placing red structural concrete on cast day

The sanding process was initiated after a 21-day cure starting with a wet sand (utilized to reduce exposure to dust particles containing calcium hydroxide and crystalline silica, providing a safer work environment) of the outside with 80-grit sandpaper. A patching structural mix was applied to fill inconsistencies at 28-days after the curing chamber was turned off. The canoe was then turned over so that the mold could be removed from the concrete by cutting the foam out from the inside, but leaving 2 feet of foam in each bulkhead. The remainder of the bulkhead concrete was then placed using both structural and aesthetic pigmented mixes and the inside of the canoe was patched and wet-sanded with the same variety of sandpaper as the outside to ensure the smoothest surface possible. Adhesive appliques were applied by hand to the canoe after sanding was completed and the canoe was sealed using EverClear 350 acrylic sealant.

The team improved upon safety by utilizing Arizona State University's hazardous waste disposal program to properly dispose of expired admixtures, old concrete specimens, and other waster from mold construction. All team members and volunteers were required to wear close-toed shoes, long pants, gloves, safety glasses, and respirators when working with the mold and the concrete. Overall, the team succeeded in improving upon last year's construction techniques, saving time, materials, and cost, while improving upon quality and safety. *The Maroon Machine* was created to be and created by the best that the ASU ASCE chapter has to offer, and will leave all the other teams saying "we would've won, too, if it weren't for you meddling kids."

This year's Project Management (PM) team focused on recruiting and incorporating new captains and team members into the process, on equitably distributing work amongst the team, and on improving communication and meeting deadlines. The canoe's leadership team consisted of six members: one construction and hull design project manager, one mix design project manager, one hull design captain, one construction captain, one mix design captain, and one paddling captain. The project managers and paddling captain were chosen because of their previous experience on the team, with the remaining members being chosen because of their interest in and enthusiasm for the project. Additional dedicated team members joined the mix design and construction processes in the Fall semester to help the captains and project managers complete tasks as deadlines approached.

An initial meeting was held after the end of the 2018 Pacific Southwest Conference to transition between old and new PM's, to draft a schedule of primary goals for the next year, and to acquaint the new team with necessary deliverables. Once the 2018-2019 academic year began, initial meetings were held to incorporate the new members into the team, introduce them to the project, and finalize a project schedule and project goals as seen in Table 8. Meetings were then held on an as-needed basis, opting for instant messaging and emailing to give weekly updates, with all captains reporting directly to the PM's, and the PM's consolidating and disseminating the information to the rest of the team.

Table 8. Project Milestones

Milestone	Delay	Cause
Hull Design	None	-
CNC Mill the Mold	2 weeks	Machine failure and transportation issues
Finalize Mix Design	6 weeks	Funding issues, discontinued materials, workability issues
Casting the Canoe	1 week	Better date for more volunteer participation

After reviewing the flawed schedule from the previous year that saw many delays and rushed final products, this year's schedule was designed conservatively with large margins of error to account for any problems encountered and to allow for additional time to perfect final products. This critical path was determined from lessons learned in previous years and was organized in a way that allowed for multiple tasks to be completed in parallel. Most of the initial milestones were scheduled for completion before major academic breaks to allow for large time cushions and to ensure that milestones further along in the project would not be significantly impacted by the delays in the preceding steps. Moreover, the internal deadline for completion of the design report was set early for review and editing by other members of the team and experienced alumni. This deadline was met by allocating sections to team members outside of the PM's and by establishing strict expectations to ensure each member completed their deliverable.

The first priority for the PM's was to create a budget for all supplies and expenditures for the academic year using the previous year's budget sheets and bank statements as a baseline which determined the amount of sponsorship that was needed from local companies and from the school to fund the canoe. A major impediment to the development and testing was a lack of funds at the beginning of the semester caused by severe deficits in the account at the start of the year. This discrepancy between what was in the account and what was thought to be in the account led the PM team to create a comprehensive budget sheet to monitor the expenses incurred, the sponsorship received, the reimbursements delivered, and future costs. The breakdown of the anticipated and actual budgets is shown in Figure 9. The process was made more economical by receiving donations of cementitious materials (such as OPC and fly ash) and aggregates, and by utilizing free training and usage of an on-campus milling machine.

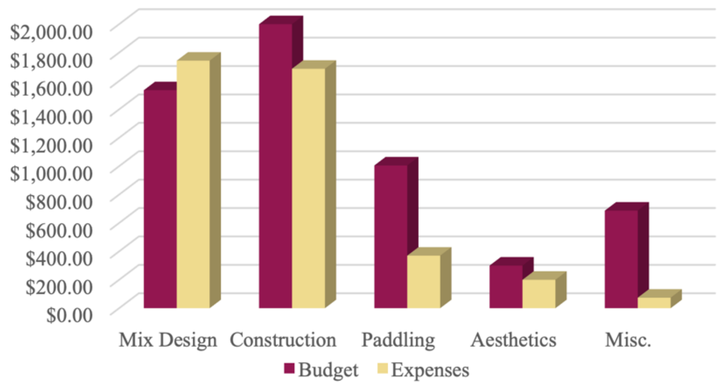


Figure 9. Budget and Expenditure Estimates

After the release of the rules, the team officially began on the project and started work on mix design and mold construction. Mix design development experienced delays because materials could not be purchased due to funding issues and because some materials used in the initial mixes could not be re-ordered or had to be replaced with different materials. The CNC milling of the canoe mold experienced delays because the CNC machine was not leveled properly and broke multiple drill bits needed for cutting and because alternate material transportation to the ASU Innovation Hub that housed the machine had to be arranged to save on costs. The construction of the mold was also offset by a few weeks because of the lack of manpower in sanding and finishing the mold for cast day. Cast day was one week behind schedule so that the cast date was at an optimal time for the largest amount of volunteers to attend, and thus was rescheduled to not coincide with a long weekend. Despite the delays, the team worked hard to meet deadlines and produce quality deliverables, using 1070 person-hours to complete the task, with the allocation of work hours shown in Figure 10.

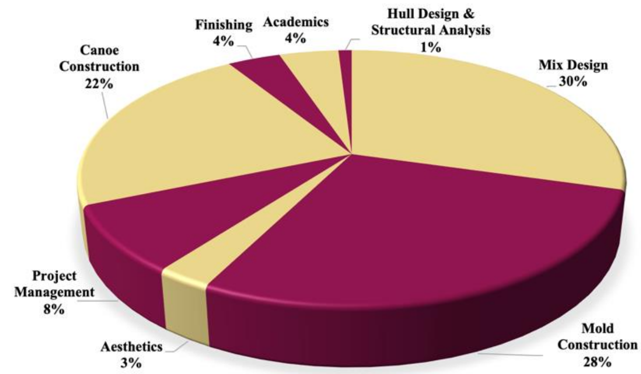


Figure 10. Person Hour Allocation

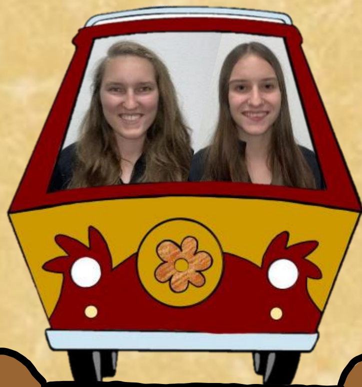
Even though the project was occasionally behind schedule, quality was never sacrificed for speed. Quality controls including many pre-training sessions to ensure that all members were properly briefed on the goals for the final product and how to achieve those goals. For mix design, this meant that the project manager trained three other mix design members how to properly, efficiently, and autonomously mix a batch of concrete using test mixes as practice. Every batch mixed before and during cast day was quality checked by both project managers before placement on the mold to ensure that the workability and color were consistent and acceptable for use. Due to non-compliance last year, quality controls ensured that all materials used in the mix were approved for use in comparison to the rules. For construction, this meant that all members were supervised by the PM during the initial stages of a new construction phase to ensure that the final product was compliant with the rules and with the desired outcome. Due to poor quality of the final mold last year before casting, more time was put into sanding the Styrofoam, sanding the individual FoamCoat layers (including using an orbital sander for the smoothest finish), and applying more layers of releasing agent. Moreover, there were two pre-training sessions before cast day for the volunteers to teach them how to apply concrete to the mold and minimize unevenness, slumping, and air pockets.

Safety was a priority throughout all processes and new safety procedures were implemented to avoid non-compliance in previous years. All PM’s and captains were required to participate in fire safety training and proper silica handling training which prompted the PM’s to procure more comprehensive personal protective equipment (PPE) such as contoured safety goggles (as opposed to safety glasses), better face masks/respirators, and thicker disposable gloves, as well as more strictly enforcing the usage of long pants and close-toes shoes. The team worked closely with facilities management to safely dispose of old concrete waste, unlabeled materials and chemicals, Styrofoam remnants, and a decommissioned canoe. The team worked with the ASU ASCE elected student Facilities Manger to ensure compliance with fire exits, cleared walkways, electrical cabinet accessibility, fire hazards, and cleanliness.

For sustainability, in addition to the aspects mentioned previously, other measures were taken to reduce waste. The aesthetics team repurposed display components from last year, such as repainting large wood panels for a mural. Mix design increased sustainability by reusing concrete cylinders for testing and by using last year’s remaining pre-batches to train new mix volunteers before starting testing.

The communication, scheduling, budgeting, quality control, sustainability, and safety used by the project management team streamlined the process and helped create a well-managed and well-made canoe.

Organization Chart



(L) Brielle Januszewski (Jr)
(R) Hilary Merline (Sr)

PROJECT MANAGEMENT

Responsible for scheduling, fundraising, task delegation, rule compliance, quality control, safety, and material procurement

Mark Natale (Sr)

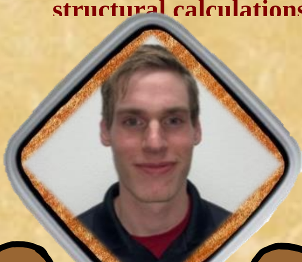
HULL DESIGN CAPTAIN

Responsible for design and analysis of the hull, determining strength requirements, and performing structural calculations

Alexandra Brown (Fr)

MIX DESIGN CAPTAIN

Responsible for research and development of concrete and performing laboratory testing



Michael Kasner (Jr)

CONSTRUCTION CAPTAIN

Responsible for mold construction, concrete casting, and finishing, and curing chamber construction

Austyn Howard (Sr)

PADDLING CAPTAIN

Responsible for coordinating practices and tryouts, and teaching paddling techniques

Camila Ibarra (So)

AESTHETICS CAPTAIN

Responsible for designing and producing canoe display and report design

FACULTY ADVISORS
Christopher Lawrence
Narayanan Neithalath
Kristen Ward

MIX DESIGN
Sam Suwarno

CONSTRUCTION
Shaela Hogue
Zakariya Al-Hinai

AESTHETICS
Austyn Howard
Nancy Rodriguez
Grayson Weinburger

PADDLERS
Alexandra Brown
Joseph Herrera-Theut
Austyn Howard
Brielle Januszewski
Michael Kasner
Hilary Merline
Mark Natale
Maximilian Porte
Amy Santilli

PRESENTATION
Alexandra Brown
Brielle Januszewski
Mark Natale

GRAPHIC DESIGN
Camilla Ibarra

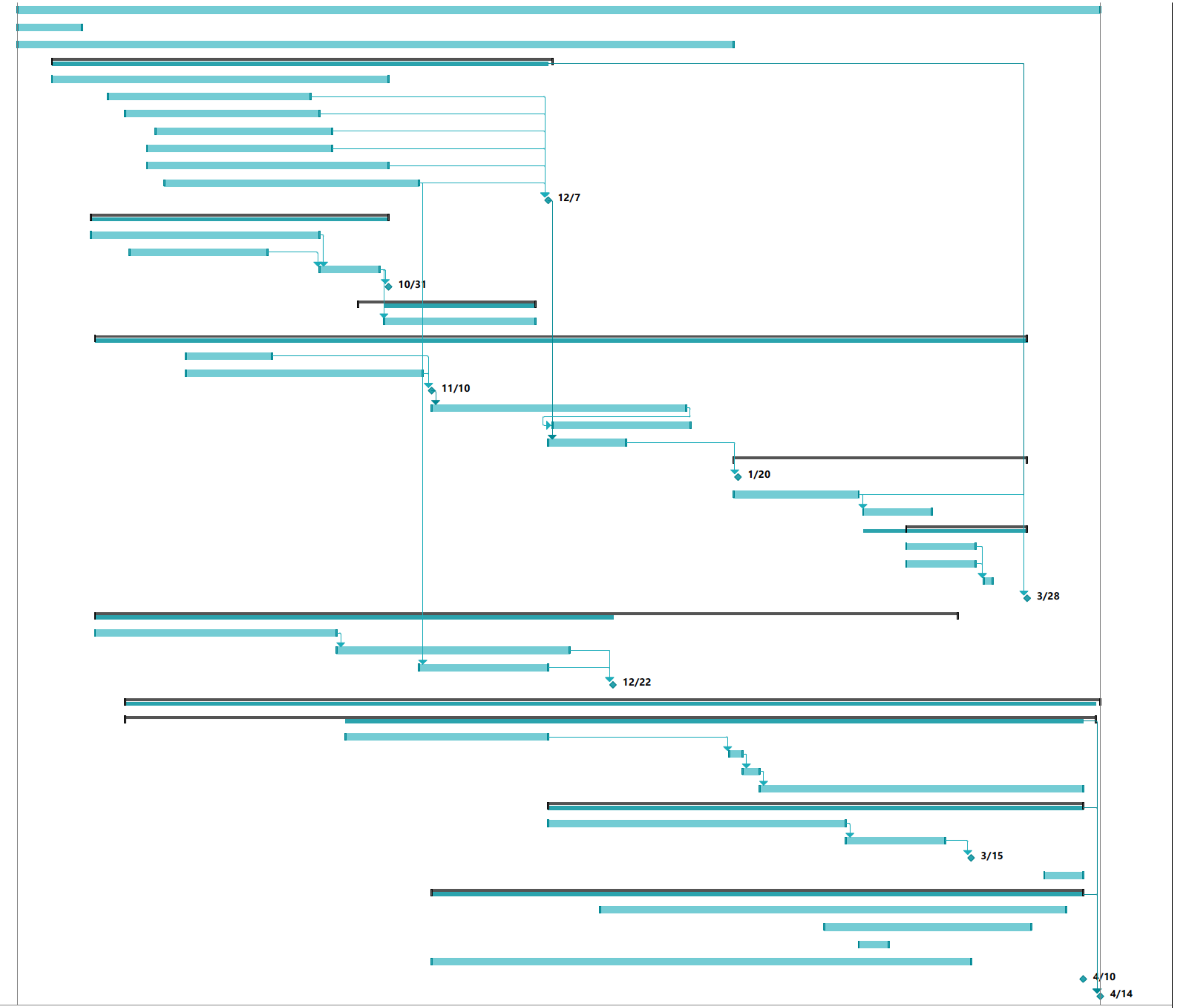
SAFTEY OFFICER
Hilary Merline

FACILITIES MANAGER
Nicole Trujillo

ALUMNI ADVISORS
Cesar Castro
Ian Contreras
Connor Fegard
Victoria Flys
Natalie Miller

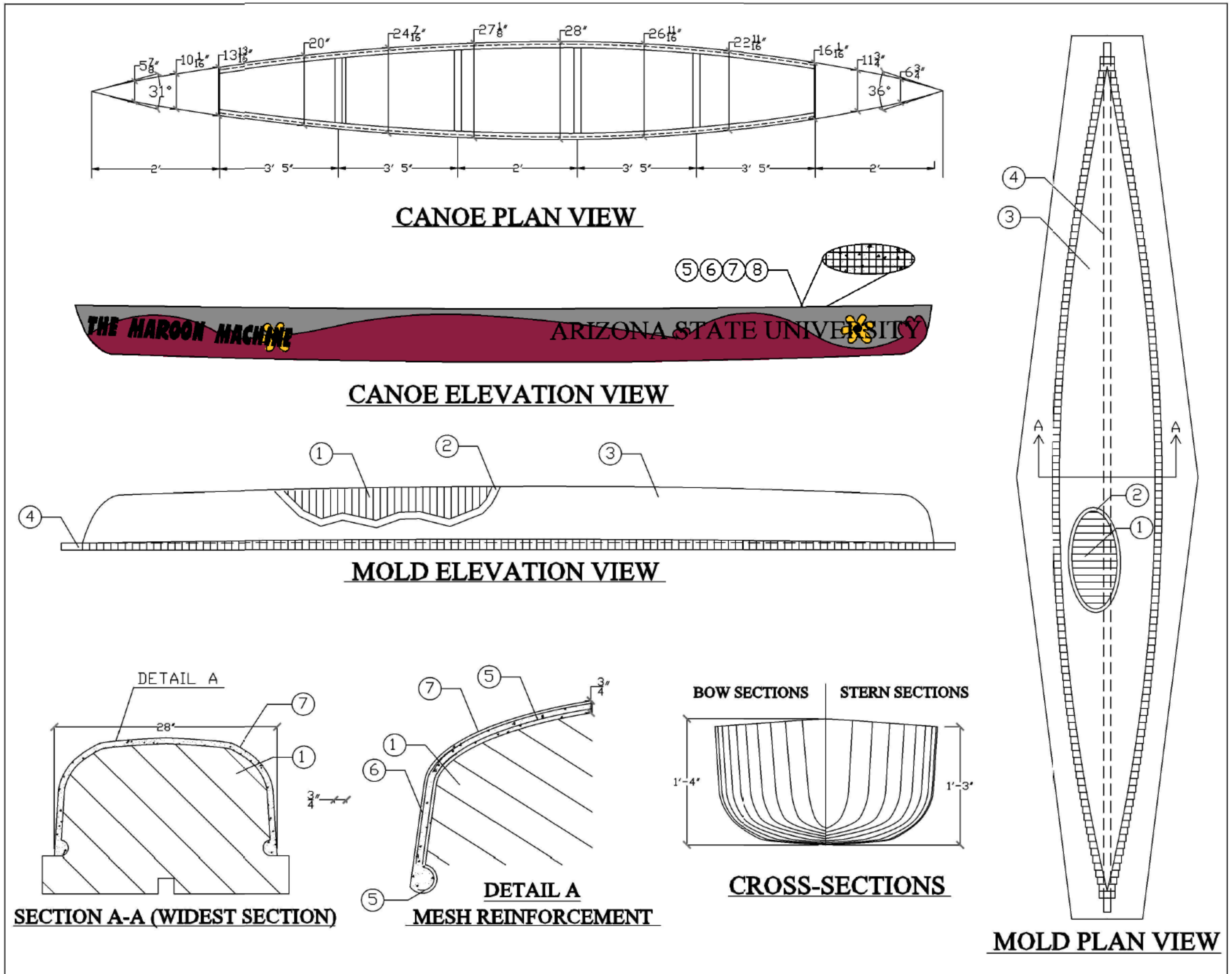
Project Schedule

1	**Concrete Canoe 2018**	184 days	Mon 8/7/17	Sat 4/14/18	Mon 8/14/17
2	**Performance Review**	11 days	Mon 8/7/17	Mon 8/21/17	Mon 8/14/17
3	**Project Planning & Research**	122 days	Mon 8/7/17	Fri 1/19/18	Mon 8/14/17
4	**Mix Design**	**86 days**	**Tue 8/15/17**	**Fri 12/8/17**	**Tue 8/15/17**
5	Materials Procurement	57 days	Tue 8/15/17	Tue 10/31/17	Tue 8/15/17
6	Materials Testing	35 days	Mon 8/28/17	Fri 10/13/17	Mon 8/28/17
7	Baseline Mixes	32 days	Fri 9/1/17	Sun 10/15/17	Mon 9/4/17
8	Cementious Materials Testing	29 days	Fri 9/8/17	Wed 10/18/17	Fri 9/8/17
9	Aggregate Testing	31 days	Wed 9/6/17	Wed 10/18/17	Wed 9/6/17
10	Admixture Testing	41 days	Wed 9/6/17	Tue 10/31/17	Wed 9/6/17
11	Fiber & Mesh Testing	44 days	Sun 9/10/17	Tue 11/7/17	Sun 9/10/17
12	Final Mix Selection	23 days	Wed 11/8/17	Thu 12/7/17	Wed 11/8/17
13	**Hull Design**	**50 days**	**Thu 8/24/17**	**Tue 10/31/17**	**Thu 8/31/17**
14	Develop MATLAB Program	38 days	Thu 8/24/17	Sun 10/15/17	Thu 8/31/17
15	Drafting & Modeling	23 days	Sat 9/2/17	Tue 10/3/17	Fri 9/1/17
16	Finalize Design	11 days	Mon 10/16/17	Sun 10/29/17	Thu 9/28/17
17	CNC Drafting	1 day	Tue 10/31/17	Tue 10/31/17	Tue 10/3/17
18	**Structural Analysis**	**31 days**	**Wed 10/25/17**	**Mon 12/4/17**	**Wed 10/25/17**
19	Finalize Analysis	26 days	Tue 10/31/17	Mon 12/4/17	Tue 10/31/17
20	**Construction**	**157 days**	**Fri 8/25/17**	**Wed 3/28/18**	**Fri 8/25/17**
21	Small Scale Testing	14 days	Fri 9/15/17	Wed 10/4/17	Fri 9/15/17
22	Material Procurement	40 days	Fri 9/15/17	Wed 11/8/17	Fri 9/15/17
23	CNC Form	1 day	Fri 11/10/17	Fri 11/10/17	Fri 11/10/17
24	Mold Construction	42 days	Sat 11/11/17	Mon 1/8/18	Sat 11/11/17
25	Finish Mold	23 days	Sat 12/9/17	Tue 1/9/18	Sat 12/9/17
26	Prebatching for Cast Day	12 days	Fri 12/8/17	Mon 12/25/17	Fri 12/8/17
27	**Casting Concrete**	**49 days**	**Sat 1/20/18**	**Wed 3/28/18**	**Sat 1/20/18**
28	Cast Day	1 day	Sat 1/20/18	Sat 1/20/18	Sat 1/20/18
29	Curing	22 days	Sat 1/20/18	Sat 2/17/18	Sat 1/27/18
30	Form Removal	12 days	Mon 2/19/18	Tue 3/6/18	Mon 3/12/18
31	**Finishing**	**20 days**	**Thu 3/1/18**	**Wed 3/28/18**	**Thu 3/1/18**
32	Patching/Sanding Exterior	12 days	Thu 3/1/18	Fri 3/16/18	Mon 2/26/18
33	Patching/Sanding Interior	12 days	Thu 3/1/18	Fri 3/16/18	Thu 3/15/18
34	Sealing	2 days	Mon 3/19/18	Tue 3/20/18	Mon 3/19/18
35	Finished Product	28 days	Mon 2/19/18	Wed 3/28/18	Mon 2/19/18
36	**Aesthetics**	**145 days**	**Fri 8/25/17**	**Mon 3/12/18**	**Fri 8/25/17**
37	Theme Selection	40 days	Fri 8/25/17	Thu 10/19/17	Fri 8/25/17
38	Design Sketching & Planning	40 days	Fri 10/20/17	Tue 12/12/17	Fri 10/20/17
39	Pigment Testing	23 days	Wed 11/8/17	Thu 12/7/17	Wed 11/8/17
40	Finalize Theme Designs	7 days	Thu 12/14/17	Fri 12/22/17	Thu 12/14/17
41	**Conference Preperation**	**165 days**	**Fri 9/1/17**	**Sat 4/14/18**	**Fri 9/1/17**
42	**Paddling**	**164 days**	**Fri 9/1/17**	**Fri 4/13/18**	**Fri 9/1/17**
43	Information Sessions & Open Training	37 days	Sun 10/22/17	Thu 12/7/17	Sun 10/15/17
44	Tryouts	3 days	Fri 1/19/18	Sun 1/21/18	Sat 2/10/18
45	Team Selection	4 days	Mon 1/22/18	Thu 1/25/18	Sun 2/11/18
46	Practice	53 days	Fri 1/26/18	Tue 4/10/18	Sat 2/17/18
47	**Design Paper**	**89 days**	**Fri 12/8/17**	**Tue 4/10/18**	**Fri 12/8/17**
48	Rough Draft	50 days	Fri 12/8/17	Wed 2/14/18	Fri 12/8/17
49	Final Draft & Editing	17 days	Thu 2/15/18	Fri 3/9/18	Wed 2/28/18
50	Send Paper	2 days	Wed 3/14/18	Thu 3/15/18	Wed 3/14/18
51	Rehearse Technical Presentation	7 days	Mon 4/2/18	Tue 4/10/18	Sat 3/31/18
52	**Final Product Display**	**109 days**	**Sat 11/11/17**	**Tue 4/10/18**	**Sat 11/11/17**
53	Construct stand	79 days	Wed 12/20/17	Fri 4/6/18	Wed 12/20/17
54	Construct Table Display	35 days	Sat 2/10/18	Thu 3/29/18	Fri 3/16/18
55	Cutaway	7 days	Sun 2/18/18	Sat 2/24/18	Mon 3/26/18
56	Engineer's Notebook	91 days	Sat 11/11/17	Thu 3/15/18	Sat 11/11/17
57	Complete Display	7 days	Mon 4/2/18	Tue 4/10/18	Wed 4/4/18
58	**Attend PSWC at ASU**	**4 days**	**Wed 4/11/18**	**Sat 4/14/18**	**Wed 4/11/18**



Project: 2018 ASU Canoe Prelim
Date: Wed 2/27/19

Milestone ◆ Summary Task Baseline



BILL OF MATERIALS

Part	Qty	Description
1	120	EXPANDED POLYSTYRENE FOAM
2	3 gal	FOAM COAT
3	65 sf	RELEASING AGENT
4	1	HSS 2"X2"X23'-0"
5	85 sf	FIBERGLASS MESH LAYER 1
6	80 sf	FIBERGLASS MESH LAYER 2
7	5.11 ft^3	Concrete (Per Mix Design Appendix B)
8	2 gal	BARACADE WB 244 SEALER

THE MAROON MACHINE

DESIGN BY:	AUSTYN HOWARD
DRAWN BY:	MARK NATALE
APPROVED BY:	MARK NATALE
SCALE:	NTS
SUBMITTED: 3/5/2019	PAGE: 12

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Appendix B – Mixture Proportions

Cementitious Materials				
Component	***Specific Gravity***	***Volume (ft^3)***	***Amount (mass/volume) (lb/yd^3)***	
Ordinary Portland Cement, ASTM Type I	3.15	1.567	*307.98*	*Mass of all cementitious materials, cm* ***632.17*** *lb/yd^3* *w/cm ratio* ***0.32***
Class F Fly Ash	2.30	1.129	*162.09*	
Metakaolin	2.50	0.416	*64.84*	
VCAS-160	2.60	0.599	*97.26*	

Fibers			
Component	***Specific Gravity***	***Volume (ft^3)***	***Amount (mass/volume) (lb/yd^3)***
GRACE Micro Fibers	0.91	0.055	*3.10*

Aggregates							
Aggregates	***Abs (%)***	***MC_{stk} (%)***	***SG***	***Base Quantity (lb/yd^3)***		***Volume, SSD (ft^3)***	***Batch Quantity (at MC_{stk}) (lb/yd^3)***
				OD	***SSD***		
Clay Shale (Fine)	*80.0*	6.62	0.85	*60.85*	*109.53*	*2.011*	*107.173*
Clay Shale (Crushed Fine)	*80.0*	9.33	0.84	*40.79*	*73.43*	*1.363*	*71.854*
Clay Shale (10 Mesh)	*80.0*	8.39	0.83	*20.05*	*36.09*	*0.686*	*35.318*
Poraver (0.1-0.3)	*70.0*	0.31	0.90	*58.57*	*99.57*	*1.735*	*97.430*
Poraver (0.25-0.5)	*60.0*	0.31	0.68	*23.34*	*37.34*	*0.861*	*36.536*
Poraver (0.5-1.0)	*50.0*	0.31	0.47	*99.57*	*149.36*	*4.983*	*146.145*
Poraver (1.0-2.0)	*40.0*	0.31	0.41	*35.56*	*49.79*	*1.908*	*48.809*

Admixtures					
Admixture	***lb/gal***	***Dosage (fl.oz/cwt)***	***% Solids***	***Water in Admixture (lb/yd^3)***	
AEA 92	*8.5*	*9.0*	*6.0*	*3.54*	*Total Water from All Admixtures* ***4.26*** *lb/yd^3*
Plastol 6400	*8.8*	*2.5*	*36.0*	*0.72*	

Solids (latex, dyes and powdered admixtures)			
Component	***Specific Gravity***	***Volume (ft^3)***	***Amount (mass/volume) (lb/yd^3)***
Davis Colors Powdered Pigment (Black)	*4.80*	*0.0*	
Color-crete Granular Red 110	*1.08*		
Color-crete Granular Yellow 920	*0.96*		
3M Glass Bubbles	*0.15*	*2.602*	*24.357*

Water		
	Amount (mass/volume) (lb/yd^3)	***Volume (ft^3)***
Water, lb/yd^3	*396.26*	*9.41*
Total Free Water from All Aggregates, lb/yd^3	*182.72*	
Total Water from All Admixtures, lb/yd^3	*8.32*	
Batch Water, lb/yd^3	*587.30*	

Densities, Air Content, Ratios and Slump						
	cement	***fibers***	***aggregates***	***solids***	***water***	***Total***
Mass of Concrete, M, (lb)	632.17	3.1	543.27	25.0	*378.69*	*1582.21*
Absolute Volume of Concrete, V, (ft^3)	3.711	*0.055*	*13.55*	*2.61*	*3.14*	*23.065*
Theoretical Density, T, *(= M / V)*	68.60	*lb/ft^3*	***Air Content*** *[= (T – D)/D x 100%]*			*14.57%*
Measured Dry Density, D	60.58	*lb/ft^3*	***Slump, Slump flow***			*0 in.*
water/cement ratio, w/c:	0.487		***water/cementitious material ratio, w/cm:***			0.32

(1) The first step was to determine batch volume. For purposes of testing, 0.1 ft^3 was chosen.
(2) A w/cm ratio of 0.31 was selected from extensive testing.
(3) Optimal gradation was found using a 0.45 power chart. From experimentation, the ratios were optimized for the aggregate and cementitious material amount (lb/yd^3)

Aggregates	Fine Shale	Crushed Fine Shale	10 Mesh Shale	Poraver (0.1 – 0.3)	Poraver (0.25 – 0.5)	Poraver (0.5 – 1.0)	Poraver (1.0 – 2.0)
% Volume	12.5	8.4	4.2	10.7	5.3	30.9	11.8

Cementitious Materials	OPC	Fly Ash	Metakaolin	V-CAS
% Volume	42.2	30.4	11.2	16.2

(4) Following the same order as in Step 3, the percentages translate to amounts:

Aggregates	Fine Shale	Crushed Fine Shale	10 Mesh Shale	Poraver (0.1 – 0.3)	Poraver (0.25 – 0.5)	Poraver (0.5 – 1.0)	Poraver (1.0 – 2.0)	Total
Amount (lb/yd^3)	107.173	71.854	35.318	97.430	36.536	146.145	48.809	567.62

Cementitious Materials	OPC	Fly Ash	Metakaolin	V-CAS	Total
Amount (lb/yd^3)	307.98	162.09	64.84	97.26	632.17

(5) Batch weight found for each material

Weight = $\frac{Amount\ (batch\ volume)}{27\ ft^3/yd^3}$

Aggregates:
Fine Shale = (107.173)(0.13) = 13.93 lb
Crushed Shale = (71.854)(0.13) = 9.34 lb
10 Mesh = (35.318)(0.13) = 4.59 lb
Poraver (0.1 – 0.3) = (97.430)(0.13) = 12.67 lb
Poraver (0.25 – 0.5) = (36.536)(0.13) = 4.75 lb
Poraver (0.5 – 1.0) = (146.145)(0.13) = 19 lb
Poraver (1.0 – 2.0) = (48.809)(0.13) = 6.35 lb

Cementitious Materials:
OPC = (307.98)(0.13) = 40.04 lb
Fly Ash = (162.09)(0.13) = 21.07 lb
Metakaolin = (64.84)(0.13) = 8.43 lb
V-CAS = (97.26)(0.13) = 12.64 lb

(6) To find batch volume, the specific gravity of the materials was obtained from manufacturers.

Aggregates	Clay Shale (Fine)	Clay Shale (Crushed Fine)	Clay Shale (10 Mesh)	Poraver (0.1 – 0.3)	Poraver (0.25 – 0.5)	Poraver (0.5 – 1.0)	Poraver (1.0 – 2.0)
G	0.854	0.845	0.825	0.9	0.68	0.47	0.41
Batch Weight (lb)	0.516	0.346	0.170	0.469	0.176	0.704	0.235
Batch Volume (ft^3)	0.010	0.007	0.003	0.008	0.004	0.024	0.009

Cementitious Materials	OPC	Fly Ash	Metakaolin	V-CAS
G	3.15	2.30	2.50	2.60
Batch Weight (lb)	1.483	0.78	0.312	0.468
Batch Volume (ft^3)	0.008	0.005	0.002	0.003

(7) 0.15 lb of glass fibers are then added from experimental results

(8) Water for Cement Hydration:
W_C = (Cementitious Amount lb/yd³)(w/cm)
W_C = (632.17)(0.31) = 195.97 lb/yd³

Water for Aggregates:
W_A = (Aggregate Amount lb/yd³)(% Absorption)
$$W_A = \frac{97.430(70.0) + 36.536(60.0)+146.145(50.0)+48.809(40.0)}{100}$$
W_A = 182.72 lb/yd³

(9) Batch volume of water
Water for Aggregates SSD:

$$B_A = \frac{(182.72\frac{lb}{yd^3})(0.13\ ft^3)}{27\ ft^3/yd^3} = 0.880 \text{ lb}$$

(10) Admixtures are added by dosages of mL, and were determined from previous experimental data:

Admixture	AEA 92	SPC
Batch Volume (mL)	9	2.5
Weight of Water (lb)	3.93	0.80

$\sum Weight\ of\ Water\ (lb) = \sum 3.54 + 0.72 = 4.65$ lb

(11) Total water accounting for admixtures is then calculated:

W_{AD} = W_C – 4.65 lb

= 195.97 lb - 4.65 lb
= 191.32 lb/yd³

$B_{AD} = \frac{(191.32 \text{ lb/yd}^3)(0.13 \text{ ft}^3)}{27 \text{ ft}^3/\text{yd}^3} = 0.921$ lb

$\text{w/c} = \frac{W_C + W_A}{632.17 \text{ lb/yd}^3} = 0.60$

$\text{w/cm} = \frac{W_C}{632.17 \text{ lb/yd}^3} = 0.31$

(12) Wet unit weight was found experimentally right after mixing the concrete:

3x6 cylinder: $V = \frac{\pi(1.5\ in)^2(6\ in)}{(12\ in/ft)^3} = 0.0245\ ft^3$

γ_1= 1.456 lb / 0.0245 ft^3 = 59.43 pcf
γ_2= 1.567 lb / 0.0245 ft^3 = 63.96 pcf
γ_3= 1.557 lb / 0.0245 ft^3 = 63.55 pcf
γ_4= 1.586 lb / 0.0245 ft^3 = 64.73 pcf
γ_{actual} = 62.92 pcf

(13) Gravimetric Air Content

$$A = \left[\frac{\gamma_{theoretical} - \gamma_{actual}}{\gamma_{theoretical}}\ x\ 100\right] = \left[\frac{68.6\ pcf - 62.92\ pcf}{68.6\ pcf}\ x\ 100\right]$$

A = 8.30 %

Shear Stress in Chine and Deflection in Gunwale

For chine shear stress and gunwale deflection, water unit weight was estimated to be 63 pcf, and increased linearly to the depth where the cut was made. Since there is no external force opposing the water pressure, the shear force is equal and opposite to the water pressure. To find gunwale deflection, moments were summed about the cut at the chine. From the moment equation, the rotation equation, $\theta(x)$ can be computed by integrating the moment equation. The deflection equation, $w(x)$, can be computed by integrating the rotation equation. Both rotation and deflection need to be divided by the product of the modulus of elasticity (E) and moment of inertia (I).

Modulus of elasticity was found through ACI 19.2.2.1. Although this code is only for concrete with unit weights between 90-150 lb/ft^3, it was assumed that this would work for work for our low-density concrete. Moment of inertia was computed by assuming the sidewall of the canoe was a rectangle with thickness 0.75in and length 20ft.

Table 9. Structural Calculation Values

Property	Value
Max Depth	15 in
Height, H	14.25 in
Thickness, t	0.75 in
γ_{water}	63 lb/ft^3
Shear Area, A_v	180 in^2
Average Shear Stress, τ	6.3 psi
Gunwale Deflection, w	0.014 in
Modulus of Elasticity, E	485000 psi
Moment of Inertia, I	8.44 in^4

Max depth of canoe: $15 in$

Canoe Thickness: $3/4 in$

Depth of Chine: $14.25 in$

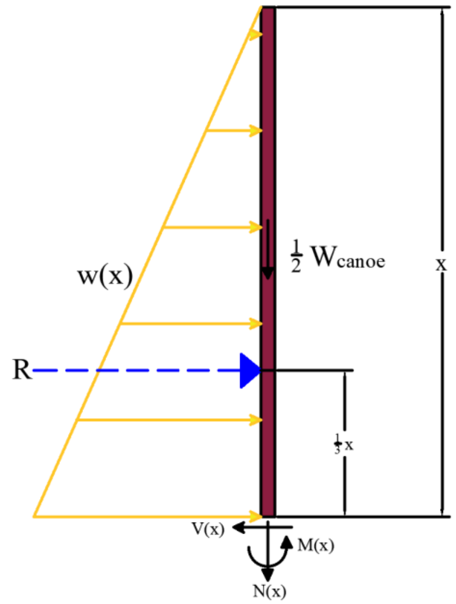
$$\gamma_{water} = 63\frac{lb}{ft^3} = 0.036\frac{lb}{in^3}$$

$$R = .5(\gamma H)(A)$$

Multiply γH by 1.3 to account for dynamic wave action

$$H = x\ in$$
$$A = (20')(x) = (240")(x)$$

$$R = 5.616x^2$$



Shear Stress in Gunwale

Force Summation

$$\sum F = R - V(x) = 0 \qquad V(x) = R = 5.616x^2$$

Chine is located at $x = 14.25”$

$$V(14.25) = 1141\ lbs$$

Shear Area, A_v

$A_v = (L)(t) = (240")(.75") = 180in^2$

$\tau = \frac{V}{A_v} = \frac{1141\ lbs}{180in^2} = \boldsymbol{6.3\frac{lb}{in^2}}$

Shear Stress in Chine is approximately 6.3 psi

Gunwale Deflection

$\sum M_{cut} = m(x) - \frac{1}{3}(x)(R) = 0$ $\quad$ $M(x) = \frac{1}{3}(x)(5.616x^2) = 1.872x^3$

$EI\theta = \int M(x)dx = \int 1.872x^3dx = 0.468x^4$

$EIw = \int \theta(x)dx = \int 0.468x^4dx = 0.0936x^5$

Calculate Modulus of Elasticity – ACI 19.2.2.1

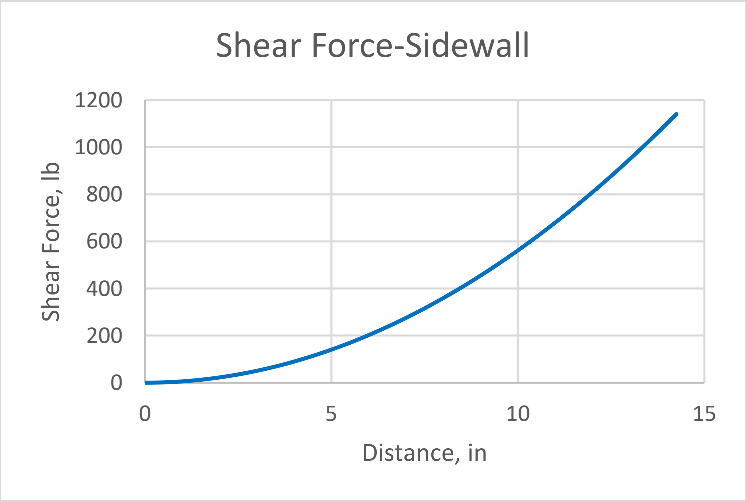
$E = w_c^{1.5}33\sqrt{f'c}$ $\quad$ $E = (60)^{1.5}33\sqrt{1000} \approx 485000\ psi$

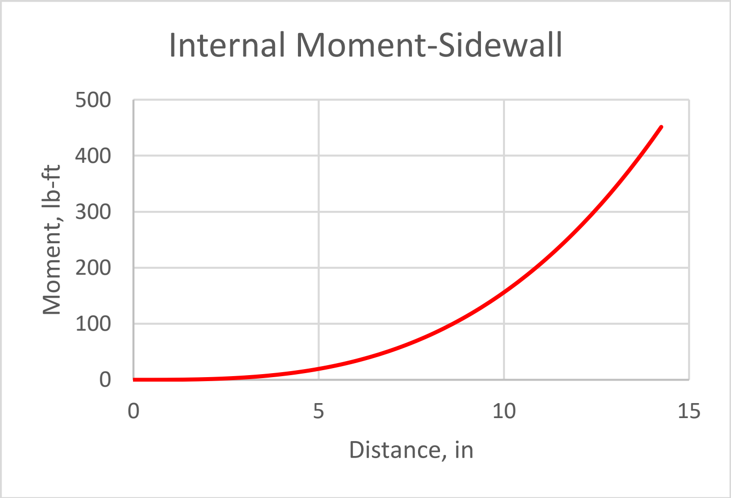
$I = \frac{1}{12}(b)(h)^3 = \frac{1}{12}(L)(t)^3 = \frac{1}{12}(240")(.75")^3 = 8.44in^4$

$EI = \left(4093400\frac{lb}{in^2}\right)(8.44in^4) = 4093400\ lb - in^2$

$w = \frac{0.0936x^5}{EI} = \frac{0.0936(14.25)^5}{4093400} = \boldsymbol{0.014}"$

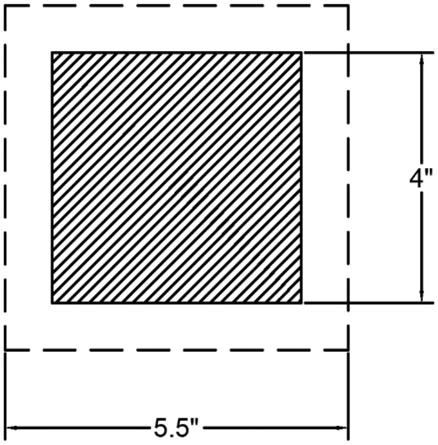
Deflection in the Gunwale is approximately 0.014”





Punching Shear

$Paddler\ Load, F = 0.75(200lb) = 150lb$



$Critical\ Perimeter, P_c = 4(4 + 2t) = 4(5.5") = 22"$

$A_v = (P_c)(t) = (22")(0.75") = 16.5\ in^2$

$Punching\ Shear, V_n = \dfrac{F}{A_v}$

$V_n = \dfrac{150lb}{16.5in^2} = \mathbf{9.1\ psi}$

Computations for shear and moment equations

Internal stresses were computed by first developing a free body diagram. The assumptions made were that the canoe acts as a beam, and the distributed load due to buoyant force is cubic . The coefficients of the cubic load were computed using a system of equations by setting the magnitude and location of the downward resultant force equal to the magnitude and centroid for a cubic function. The distributed load was also constrained to equal zero at the bow and stern. The following integrals compute the magnitude and centroid of a cubic function,

$$R = \int_0^L [ax^3 + bx^2 + cx]dx = aL^4 + bL^3 + cL^2$$
$$\bar{x}R = \int_0^L x[ax^3 + bx^4 + cx^3]dx = aL^5 + bL^4 + cL^3$$

Sum the vertical forces and moments from the FBD to compute the magnitude and location of the resultant buoyant force, then solve the system of equations.

$$+\uparrow \Sigma F_y = R - w_c L - 2W_M = 0 \qquad \Rightarrow \quad R = 650\text{ lb}$$
$$+\circlearrowleft \Sigma M_{bow} = \bar{x}R - 0.5w_c L^2 - W_M(L_1 + L_2) \ = 0 \qquad \Rightarrow \quad \bar{x}R = 6500\text{ ft}\cdot\text{lb}$$

$$\begin{array}{r} aL^3 + bL^2 + cL = 0 \\ aL^4 + bL^3 + cL^2 = R \\ aL^5 + bL^4 + cL^3 = \bar{x}R \end{array} \quad \Rightarrow \quad \begin{bmatrix} 20^3 & 20^2 & 20 \\ 20^4 & 20^3 & 20^2 \\ 20^5 & 20^4 & 20^3 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} 0 \\ 650 \\ 6500 \end{bmatrix} \quad \Rightarrow \quad \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} 0.000 \\ 0.4875 \\ -9.75 \end{bmatrix}$$

Shear force and bending moment diagrams were computed from the FBD by taking three cuts, then summing vertical forces and moments for each cut. One cut was taken before the 1st point load, one in-between the 1st and 2nd point load, and one after the 2nd point load. Example calculations for the 2nd cut are shown below. The equations for the other cuts are computed in a similar manner, the only difference being the contribution from the point loads.

$$V_2(x) = w_c x + \int_0^x [0.4875x^2 - 9.75x]dx - W_M$$
$$V_2(x) = (0.4875/3)x^3 - (9.75/2)x^2 - 12.5x - 200 \qquad 4\text{ ft} \le x \le 16\text{ ft}$$

$$M_2(x) = -0.5w_c x^2 - x\int_0^x [0.4875x^2 - 9.75x]dx + \int_0^x [0.4875x^3 - 9.75x^2]dx - W_M(x - L_1)$$
$$M_2(x) = (-0.4875/12)x^4 + (9.75/6)x^3 - 6.25x^2 - 200(x - 4) \qquad 4\text{ ft} \le x \le 16\text{ ft}$$

Hull Thickness/Reinforcement Calculations

Thickness:

Layers

Three (3) structural layers at ¼" each

Reinforcement

Two (2) layers of Fiberglass Grid White Mesh = (2)(1/128") = 0.0156"

Gunwale Rails

Rail radius = 1.0"

Wall:

Total Wall Thickness: (3)(0.25") + (0.0156") = 0.7656"

Total Mesh

Total Reinforcement Thickness = 0.0156"

Total Reinforcement Thickness/Total Wall Thickness = 0.0204 < 0.5 ***Acceptable Ratio***

Gunwale Rails and Ribs:

Total Rib Thickness: 1'' + (3)(0.25'') = 1.75''

No Rib Reinforcement

Total Rail Thickness: 1'' + (1/128'') = 129/128''

Total Rail Reinforcement: 1/128''

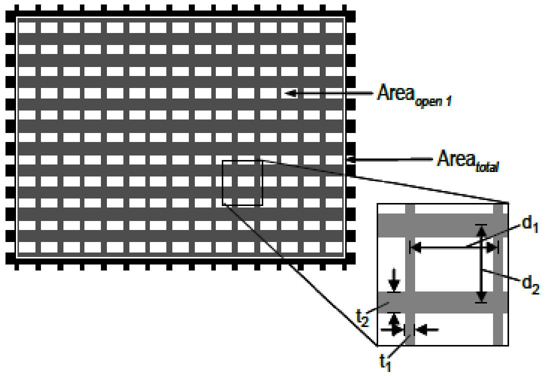
Total Reinforcement Thickness = 0.008 < 0.5 ***Acceptable Ratio***

Bulkhead:

Total Bulkhead Thickness: (3)(0.25") + (0.0156") = 0.7656"

Total Bulkhead Reinforcement: 2/128"

Percent Open Area



Annotation:
n_1: Number of apertures along sample length
n_2: Number of apertures along sample width
d_1: Spacing of reinforcing (center-to-center) along the sample length
d_2: Spacing of reinforcing (center-to-center) along the sample width
t_1: Thickness of reinforcing along sample length
t_2: Thickness of reinforcing along sample width

Equations:

$$d_1 = \text{aperature dimension} + 2(t_1/2)$$
$$d_2 = \text{aperature dimension} + 2(t_2/2)$$
$$\text{Length}_{\text{sample}} = n_1 d_1$$
$$\text{Width}_{\text{sample}} = n_2 d_2$$
$$\sum \text{Area}_{\text{open}} = n_1 \times n_2 \times \text{Area}_{\text{open 1}}$$
$$\text{Area}_{\text{total}} = \text{Length}_{\text{sample}} \times \text{Width}_{\text{sample}}$$
$$\text{POA} = \sum \text{Area}_{\text{open}} / \text{Area}_{\text{total}} \times 100\%$$

White Mesh: Mesh is made up of fiber glass and thread. The thread is woven between the fiberglass strands.

$t_1 = 2.0\text{ mm} \quad t_2 = 1.0\text{ mm}$
$d_1 = 4.0\text{ mm} + 2(2.0\text{ mm}/2) = 6.0\text{ mm}$
$d_2 = 4.0\text{ mm} + 2(1.0\text{ mm}/2) = 5.0\text{ mm}$

$$\text{Length}_{\text{sample}} = 19(6.0\text{ mm}) = 114.0\text{ mm}$$
$$\text{Width}_{\text{sample}} = 14(5.0\text{ mm}) = 70.0\text{ mm}$$
$$\sum \text{Area}_{\text{open}} = 19 \times 14 \times 16.0\text{ mm}^2 = 4{,}256\text{ mm}^2$$
$$\text{Area}_{\text{total}} = 114.0\text{ mm} \times 70.0\text{ mm} = 7{,}980\text{ mm}^2$$
$$\text{POA} = \frac{4{,}256\text{ mm}^2}{7{,}980\text{ mm}^2} \times 100\% = 53.33\ \%$$

$t_1 = 0.067\text{ in} \quad t_2 = 0.033\text{ in}$
$d_1 = 0.167\text{ in} + 2(0.067\text{ in}/2) = 0.234\text{ in}$
$d_2 = 0.15\text{ in} + 2(0.033\text{ in}/2) = 0.183\text{ in}$

$$\text{Length}_{\text{sample}} = 4(0.234\text{ in}) = 0.936\text{ in}$$
$$\text{Width}_{\text{sample}} = 4(0.183\text{ in}) = 0.732\text{ in}$$
$$\sum \text{Area}_{\text{open}} = 4 \times 4 \times 0.025\text{ in}^2 = 0.4\text{ in}^2$$
$$\text{Area}_{\text{total}} = 0.936\text{ in} \times 0.732\text{ in} = 0.685\text{ in}^2$$
$$\text{POA} = \frac{0.4\text{ in}^2}{0.685\text{ in}^2} \times 100\% = 58.4\ \%$$