

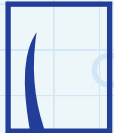
University of California **Berkeley**

SCHOOL

2006
DATE **May**

concrete canoe **technical paper**

ITEM



Caliente

Table of Contents

Executive Summary.....	i	Design Drawings and Bill of Materials	
Hull Design	1	Form.....	9
Analysis.....	2	Hull.....	10
Development and Testing.....	3	Appendix A – Mixture Proportions.....	A-1
Project Management & Construction.....	5	Appendix B – Mixture Proportions.....	B-1
Organization Chart.....	7	Appendix C – Gradation Curves	
Project Schedule.....	8	and Tables.....	C-1

Executive Summary

Located in the majestic hills across the bay from San Francisco, the University of California, Berkeley is home for those looking to excel in academics and athletics. Cal has one of the top civil engineering programs in the world providing research and applied knowledge to serve society. Reflecting the rich tradition of both academic and athletic excellence, California Concrete Canoe allows its team members to demonstrate their engineering expertise and athletic abilities in a fun and interactive environment. Cal is coming to Nationals as champion of the MidPacific Region and is proud to compete along side the University of Nevada, Reno under the Top Five Rule.

Cal has won four National Concrete Canoe championships and eleven top-five finishes, including last

Canoe Name: CALIENTE	
Max Length:	21.5 ft
Max Width:	2.6 ft
Max Depth:	12.9 in
Shell Thickness:	3/8 in
Weight:	175 lb
Color:	Blue and White
Reinforcement:	ARG Scrim
Tensile Strength:	200 ksi

Table 1 – Caliente’s Characteristics

student organized and run classes called DeCals. These classes were utilized to transfer knowledge from four-year veterans to younger team members and provide a setting to conduct structural analysis, hull design, and concrete research. The team as a whole has a healthy age gradient, an auspicious sign for future years of success for the California Concrete Canoe team.

Cal has a tradition of including Cal or Bear in its canoe name, alternating every year. Giving this Cal pun tradition a new twist, the team posted an online ballot to engage the will of the people. From six choices, the people chose the hottest name of them all, **Caliente**. This was a fun theme to implement in this year’s especially ambitious design. The interior is emblazoned with stylistic inlays throughout its length and the exterior is scorched by a raging blue fire. **Caliente** is ready to light up the competition in Stillwater.

year’s fourth place finish. Being among the most consistently competitive teams, we strive to set the standard in concrete canoe technology through constant innovation. This year the canoe benefits from foam doughnuts called **Float Rings** that serve as internal flotation located in the walls of the canoe. This innovation was conceived after last year’s canoe **Bearied Treasure** was one of the heaviest in Cal history. An innovation that mitigates risk is our newly established Disaster Fund. Also new this year are

BLUE FLAME:	
Unit Weight:	59.5 pcf
28-Day Compressive Strength:	1560 psi
28-Day Tensile Strength:	475 psi
Elastic Modulus:	1536 ksi
PALE FIRE:	
Unit Weight:	60.5 pcf
28-Day Compressive Strength:	1650 psi
28-Day Tensile Strength:	487 psi
Elastic Modulus:	1610 ksi

Table 2 – Concrete Properties



Hull Design

- Goals:** 1) Design an aggressive hull to match the ability of our experienced paddlers.
2) Optimize the canoe for weight, maneuverability, and speed.

The *Caliente* hull design is the product of thirty-five years of design and race experience. The design process began with conducting an extensive review of hull designs culled from the best of Cal and the competition. From this we found a winning canoe should value speed, weight, and maneuverability over stability. In the end, significant modifications to the base model, the 2005 canoe – *Bearied Treasure*, were adopted, including a smaller rocker, shorter overall length, greater maximum beam, asymmetry about the mid-ship, and decreased freeboard (Figure 1). These modifications were developed using Prolines hull design software.

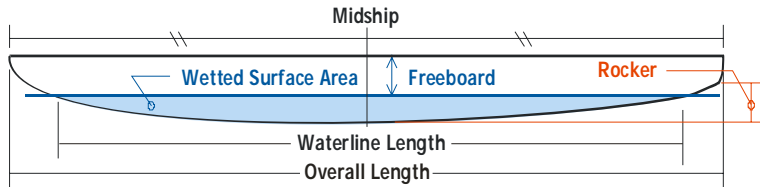


Figure 1 - Canoe Terminology

The hull design engineers reduced the rocker to $4\frac{1}{2}$ inches for the bow and $4\frac{1}{4}$ inches for the stern, thereby increasing the waterline length in all paddler scenarios. Increased waterline length improves tracking and reduces wave drag, enabling a higher maximum speed. However, the

reduced rocker proved detrimental to maneuverability (CanoeRoots 2003). One solution employed was the exertion of a greater torque on the canoe during a turn. In an asymmetrical canoe with the center of gravity aft of the mid-ship, the bow paddler has a greater lever arm, increasing the effectiveness of her plant. Another solution utilized was the increase of the maximum beam to $30\frac{3}{4}$ inches, which reduces the amount of torque required to turn.

The increased waterline length was maintained while shortening the overall length to $21\frac{1}{2}$ ft to reduce weight. The reduction in weight reduces water displacement which decreases wetted surface area and friction drag. Friction drag is directly proportional to wetted surface area and becomes the predominant retarding force at low speeds, enabling better acceleration (Lazauskas and Tuck 1996). Analysis using Prolines confirmed these results.

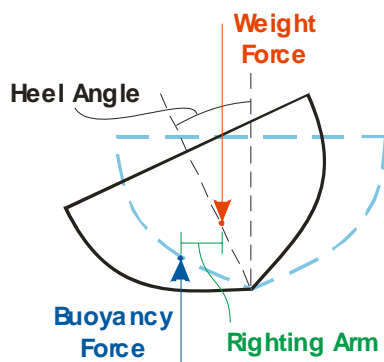


Figure 2 – Heel Diagram

The reduction in friction drag allowed us to select a relatively flat transverse cross-section shape, which slightly increases friction drag but significantly increases initial stability. Initial stability is measured by a canoe's righting arm in reaction to a small rotation about the canoe's longitudinal axis. The righting arm is the horizontal distance between the center of gravity of the canoe and the center of the reacting buoyancy force (Papoulias 2002), and is greater for flatter cross sections than rounded ones (Figure 2). Compared to *Bearied Treasure*, *Caliente's* shape gives it a greater righting arm which increases initial stability. This will minimize the impacts of decreased ultimate stability.

Ultimate stability is measured by the heel angle at which the canoe begins to take on water (Papoulias 2002). The freeboard of *Caliente* was reduced to decrease weight, giving it less ultimate stability than *Bearied Treasure*, but the design's high initial stability is sufficient to prevent water intrusion.

The changes to stability, maneuverability, speed, and weight result in a more aggressive hull geometry, allowing *Caliente's* skilled paddlers to blaze past the competition.

- Goals:** 1) Avoid significant cracking.
2) Reduce stresses in the shell by adding thickened members.

Thorough analysis and hand checks ensure the structure of *Caliente* will retain its integrity and remain crack-free under any foreseeable duress. Working stress design allows us to design for a crack-free structure by setting allowable stress values for concrete tension and compression below their respective cracking stresses. An appropriate Factor of Safety ensures that these stresses are not exceeded. The allowable stresses were set at 50% of ultimate compressive strength and at the concrete modulus of rupture, which should prevent significant cracking (Mehta and Monteiro 2006). Based on early tests, the analysis and materials engineers agreed upon initial estimates of compressive strength to be 1500 psi and modulus of rupture to be 400 psi. Initial allowable stresses were set at 750 psi in compression and 400 psi in tension. Experience suggested an additional Factor of Safety of 1.5 so that factored allowable stresses are set at 500 psi in compression and 270 psi in tension.

Using the factored allowable stresses, the first step was to check the moment demand of the canoe using a 2D beam model and check its capacity at critical cross-sections with XTRACT, a cross-section analysis tool. The canoe was first modeled by hand as a beam with a 200 lb distributed self-weight in many scenarios. The two critical cases were (1) constant pressure along the length representing water pressure with four point loads representing paddlers, resulting in a maximum positive moment demand of 6.2 kip-in and (2) linear triangular pressure distribution with two point loads, resulting in a maximum negative moment demand of 6.9 kip-in. In the initial XTRACT models, the factored allowable stresses and an estimated elastic modulus of 1400 ksi were implemented. The chosen reinforcement consisted of circular alkali resistant glass (ARG) strands with area of 0.0005 in², an elastic modulus of 10500 ksi, and ultimate tensile strength of 200 ksi. XTRACT revealed the moment capacity of the canoe at our design stresses to be ± 10 kip-in, far exceeding demand in all scenarios.

The second step was to run an iterative design/analysis procedure to find the optimal design. SAP 2000, a finite element analysis (FEA) software, was used in the Canoe Design & Analysis DeCal Class to find controlling demand moments, forces, and torques. The flexural demands were converted to stresses in XTRACT while hand calculations showed shear and torsion demands to be far less than their respective capacities. The hull was modeled in SAP as a composite shell meshed into 1406 elements with the combined properties of reinforcement and concrete in proportion to their respective areas. Thickened members (ribs and gunwales) were modeled as shell elements with increased elastic moduli to reflect their stiffnesses in the canoe. This model was analyzed under many loading scenarios, including multiple paddling cases, transportation (via the trailer and via ten people), display on stands, and submersion. Paddler loads were modeled to include the effect of paddlers shifting their weight during a race and the controlling loading case was identified as two paddlers exerting 60% of their 150 lb loads on their feet. The paddlers' knees and shins were modeled as four point loads and their feet as a uniform area loads. By recursively determining the conditions for equilibrium of the model without restraint (floating), the depth-dependent hydrostatic pressure distribution was found.

Optimizing for weight and stresses, various rib and gunwale designs were considered. Since they are stiffer than the shell, the ribs and gunwale alter load paths by attracting a larger share of forces, which in turn reduces stresses in the shell (Maekawa 2003). While these forces are of greater magnitude, they are distributed over the larger areas of the thickened elements, resulting in acceptable stresses. SAP predicted a controlling moment demand of +8 lb-in in the composite shell. Under this demand, XTRACT was used to find that the desired ultimate flexural capacity of the composite is 530 psi in tension and ultimate capacities for the concrete are 800 psi in compression and 470 psi in tension. The demand moment in the shell was checked using hand calculations at critical locations and results were comparable to those from SAP. The XTRACT results were also corroborated by hand calculations.

- Goals:** 1) Promote continuity of materials knowledge and experience.
 2) Develop concrete with high degree of workability, buoyancy, aesthetic appeal, and strength.

The *Caliente* team first addressed the goal of team continuity by establishing a DeCal course in canoe concrete. Through weekly lectures and labs, the team was able to train twice as many members as the previous year, all of whom are now educated to lead the team next year. Furthermore, the engineers kept detailed records of all mixes and tests as well as a log to guide future materials design engineers.

The procedure for mix development was to pick a promising mix, alter one component, and evaluate the results using a standardized form with predefined qualitative terms ranging from “very poor” to “very good” for workability and aesthetics, and quantitative values for strength and density. Three teams from our Canoe Concrete research class followed this procedure in weekly laboratory experiments for a total of fifty-five trials.

Baseline → Pale Fire	
Workability:	Fair/Poor → Very Good
Color:	Dark Gray → Grayish White
Strength:	3820 → 1650 psi
Modulus of Rupture:	350 → 487 psi

Table 3 – Concrete Statistics

Workability was defined by the construction engineer to be acceptable when a mix exhibited high degrees of malleability and cohesion. Qualitative measurements of these standards were recorded and each mix was accepted or rejected based on workability by the construction engineer. ATSM C143 slump measurements,

which are typically used to determine workability, were not practical given that the desired concrete mix would have zero slump. All mixes exhibit high water demand due to aggregate fineness, so we exceeded the recommended dosage of superplasticizer (9 fl oz/cwt) and ran tests to verify that our usage was not harmful. The replacement of silica fume with metakaolin resulted in significant improvements in malleability and coherence. The addition of air entraining and pigment further increased workability. For this reason, we exceeded the recommended dosage of air entrainment (3 fl oz/cwt) and carefully monitored the structural effects. For both admixtures, the manufacturer was consulted about our deviations in usage. By maximizing the workability, we were able to increase the use of fibers and therefore increase the ductility of the concrete. A trial change from class F to class C fly ash showed no improvements, and therefore was not implemented. The baseline mix was rated “fair” in malleability, “poor” in cohesiveness, and was rejected by the construction engineer. Ultimately, the final mixes were rated “very good” in each category and was accepted by the construction engineer.

Buoyancy was monitored by calculating density for each trial batch. This was an important goal, though secondary to workability. In order to obtain low specific gravities while fulfilling the required gradation, the team selected the following aggregates: K1 Glass Bubbles, Z-Light 3500 ceramic microspheres, Macrolite 1430 and Macrolite 714 ceramic spheres. Their relative proportions were first optimized within the gradation requirement for density and when trial deviations from this proportioning yielded higher densities, the optimization was verified. The binder-to-aggregate ratio was reduced until workability could no longer be achieved by adding superplasticizer. Air entraining admixture, a surfactant which allows the addition of air bubbles on the order of 3 microns, was used to further decrease density. The team increased air entrainment until strength began to control at an air content of 6.1% by ASTM C231. The baseline density was 73 pcf, and the final mixes were 60.8 pcf and 59.5 pcf, buoyant.

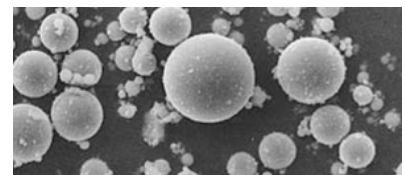


Figure 3 – SEM photo: K1 Glass Bubbles

Aesthetic appeal was evaluated by observing the color and texture of each trial batch. In order for pigment to yield a bold and consistent blue, a light base color was needed. Switching from regular Type

I/II cement to Type I white cement drastically lightened the color of the concrete. Switching to metakaolin from silica fume also lightened the unpigmented concrete. One of the reasons for the high dosage of air entrainment was the fact that microscopic air bubbles prevent the bleeding that causes pigments to run, ultimately improving the consistency of color. The baseline was dark gray while the final mixes were grayish white and blue.

Structural properties of trial batches were monitored through compressive strength (ASTM C39). Compressive strength is a good metric for many structural properties of concrete and its test is easy to perform. Mixes could be considered acceptable if they met the required strength of 800 psi. The final mixes, Pale Fire and Blue Flame, were found to have strengths of 1650 and 1560 psi, elastic moduli (ASTM C469) of 1610 and 1536 ksi, and moduli of rupture (ASTM C78) of 487 and 475 psi,

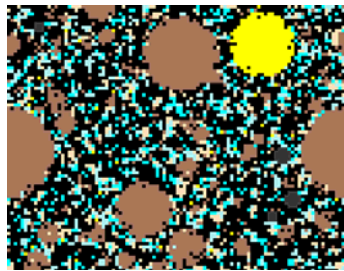


Figure 4 – Slice of 3D VCCTL Model

respectively. The moduli of rupture are efficiently in excess of the required 470 psi due to the presence of dispersed fiber reinforcement. A constitutive hybrid of 18 mm PVA (polyvinyl alcohol) microfibers and 20 mm polypropylene microfibers was used to derive a synergistic response (Banthia and Nandakumar 2003). Microfibers were used instead of conventional macrofibers because at low volume fractions the microfibers have a higher numerical density, providing over 16 million well-dispersed fibers to flank and eventually bridge microcracks at onset. The stiff PVA microfibers bridge microcracks at low crack widths promoting multiple small cracks to form rather than coalescing, enhancing the ultimate strength and crack initiation toughness of the composite. The low elastic-modulus polypropylene fibers bridge the growing microcracks at larger widths, dissipating energy through their deformation. The microfibers are also effective in decreasing drying shrinkage and thermal cracking.

Metakaolin and fly ash are both pozzolans that refine the microstructure of the concrete matrix by converting calcium hydroxide to calcium silicate hydrate. Metakaolin is also able to penetrate, refine, and densify interfacial transition zones because of its very small particle size, adding further strength and durability. These effects were explored and verified using Hydra2D and the NIST Virtual Concrete and Cement Testing Laboratory 1.1 (VCCTL).

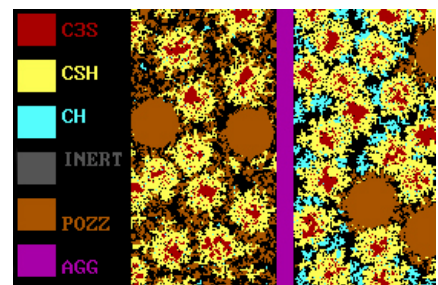


Figure 5 – Metakaolin vs. fly ash in Hydra2D

Alkali-resistant glass (ARG) scrim at 5 mm spacing was selected as primary reinforcement. This choice was based upon direct tension, pullout, and flexure tests originally performed by the *Calcatraz* team and implemented for each of the last five years. ARG scrim has an exceptional tensile strength of 200 ksi and enjoys a strong mechanical bond with concrete. Spacing of 5 mm is preferred to 10 mm because it provides additional strength and adheres more effectively to fresh concrete, facilitating placement.

The composite shell consists of three 1/8 inch layers of concrete alternating with ARG scrim. A center-point bending test (ASTM C293) gives a flexural capacity of 820 lb-in corresponding to a maximum tensile stress of 1750 psi, which exceeds the requirements suggested by the structural analysis team.

Float Rings are foam doughnuts inserted in the middle layer of the shell to add buoyancy throughout the canoe. They were found to only reduce flexural capacity by 16%, which is acceptable given their placement in the low-stress regions identified by the structural analysis team. Punching shear capacity is also reduced when the nominal diameter of force application is less than the radial width of a ring, but the doughnut geometry reduces this critical dimension by 40%.

All goals were met thanks to a well-structured development program and a knowledgeable materials team. The result is a strong, light, and eminently constructible concrete canoe.

- Goals:** 1) Mitigate risk while striving for innovation.
 2) Pass knowledge from more experienced to newer members.

The 2006 California Concrete Canoe Team utilizes a functional organizational breakdown structure. The design and work tasks were split between six functional groups: materials design, analysis & hull design, paddling, construction, fundraising, and graphics design. These groups were headed by lead engineers, many of whom were promoted from junior engineer status, utilizing the benefit of specialization that comes with a functional organization. Together, the lead engineers and project manager comprise the Executive Board, which serves as a forum for discussion and problem solving.

The first task of the team was to establish scope and goals; these were proposed for each functional group and the project manager, then deliberated by the Executive Board. Additional tasks for each functional group were to develop a safety plan according to OSHA standards, to determine a bill of materials, and to procure those materials in a manner consistent with the construction schedule.

Milestones	Variance	Reason For Variance/None
Hull Design Complete	None	On Schedule
Concrete Mix Design	None	On Schedule
Form Work	+1 Week	Delay in Casting Day
Canoe Cast	+1 Week	Resource Availability
Curing	+1 Week	Delayed with Casting Day
Canoe Finish	None	Projected for Competition

Table 4 – Milestone Activities

With a management structure and goals established, a general schedule was developed and each functional group established a detailed schedule for their specific tasks, all of which were compiled into a unified plan by the Executive Board. To check on the adherence to that plan, major milestones were determined, as well as the sequence of activities that determines

the project time, called the critical path. The critical path activities were: hull design, formwork preparation, curing, and finishing. Each month the Executive Board compared performance to the schedule. In Table 4, milestones and our performance are detailed. Considering that the inherent weakness of a functional organization is horizontal communication (Shtub et al. 1994), the Executive Board also met on a weekly basis to discuss the global view of the project, detailed look-ahead schedules, designs, safety, quality control, costs, and fundraising. The project manager was given decision-making powers to end prolonged conflicts.

With goals and a yearlong schedule established, the project manager formulated a general budget and cash flow plan. Total expenses were established by reviewing previous years' financial records and by including monthly payments to our newly established disaster fund. A capital investment in paddles was made from our savings account. To fund the expenses, the team worked with a committee of five other groups within our department to fundraise over \$83,000 of which \$22,000 was allotted to Canoe.

Innovation and change are constant for Cal Concrete Canoe, so risk management demands consideration. To reduce financial risk we established an innovative Disaster Fund. Monthly payments of \$50 were made to this fund and may be reclaimed in event of damage to or loss of team property. The budget also included a 10% contingency. To mitigate risk in the schedule, task durations were inflated. To reduce risk of competition point loss and safety, each functional group was assigned the task of establishing plans for quality assurance/quality control as well as safety for each of their tasks. The Executive Board deliberated these plans on a weekly basis.

In addition to executive meetings, the project manager coordinated team-wide activities (including casting day) and trips to the Canoe Lab in Richmond, seven miles from Berkeley's main campus. Projected to completion, 5200 person-hours were directed by the project manager.

- Goals:** 1) Improve construction techniques.
2) Develop new features.

To ensure safety during construction sessions, the *EERC Laboratory Safety Manual* was selected as a basis for our safety program.

Testing was done prior to actual construction to ensure that any unexpected problems were discovered and resolved. The first battery of tests revealed that vegetable oil performed better as a mold release agent than the traditional PVA mold release agent and several other options. Further tests identified cork sheets as a suitable material to be used to form inlays. The construction team tested foam types to find the most cost-effective and resilient material for the male form, concluding that Expanded Polystyrene Type I – Medium Density Foam was optimal. Extensive testing was done to determine the constructability and structural feasibility of including $\frac{1}{8}$ inch thick doughnut-shaped foam **Float Rings** with inner and outer diameters of $1\frac{3}{4}$ inches and $5\frac{1}{2}$ inches respectively within the canoe walls (Figure 6).



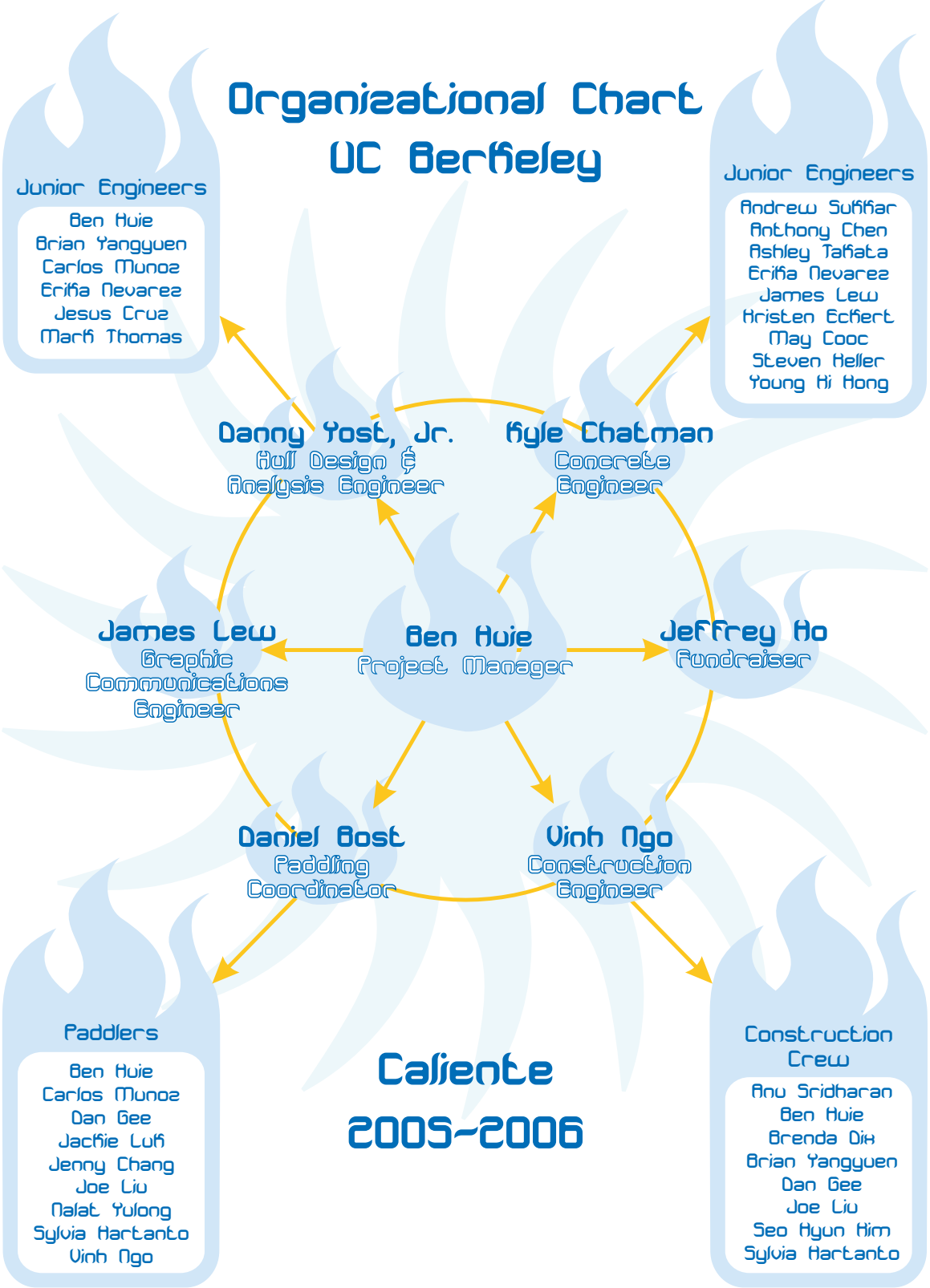
Figure 6 – Float Ring

With a 3D computer model of the hull, a male foam form was milled using a Computer Numerically Controlled drill. With the foam secured to a table, the ribs were cut with a hotwire and then the entire form was sanded smooth. Epoxy was applied to strengthen the surface before joint compound was applied to fill the imperfections inherent to the foam and was then sanded smooth again. Additional layers of epoxy were applied to create a smooth, hard surface for concrete placement. Cork sheets $\frac{1}{16}$ inch thick in the shape of the inlays were temporarily attached, and replaced with Blue Flame after curing. Finally, vegetable oil was applied to the form as a mold release agent.

Once the formwork was constructed, casting of the canoe commenced. Preparation for casting included cutting rib reinforcement, dividing members into teams, giving all members hands on experience with mixing, placing, and finishing concrete, and pre-constructing the curing tent. Placement of concrete began with the four ribs, each consisting of four alternating layers of concrete and reinforcement that extend into the gunwales one foot fore and aft from the rib. With ribs completed, the first $\frac{1}{8}$ inch layer of concrete was placed on the entire form, followed by a layer of reinforcement. For thickness control, $\frac{1}{8}$ inch thick speaker wires were placed at one-foot intervals along the length of the canoe. The speaker wires acted as guides for the rollers to level the concrete; then they were removed and backfilled. Before the second layer of concrete, reinforcement mesh was placed. The second layer included the **Float Rings** positioned in low stress areas of the wall, away from the ribs, followed by another layer of reinforcement. Before placing the last layer of concrete, a precut flame-shaped stencil was placed on the reinforcement. Blue Flame was used to backfill the void left by the removal of the stencil. The one-inch gunwale taper was placed using precut pieces of plastic-covered wood to ensure quality control and consistency. Following the completion of concrete placement, the curing tent was erected. The humidity and temperature around the concrete were monitored and corrected daily for optimal curing.

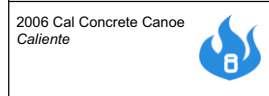
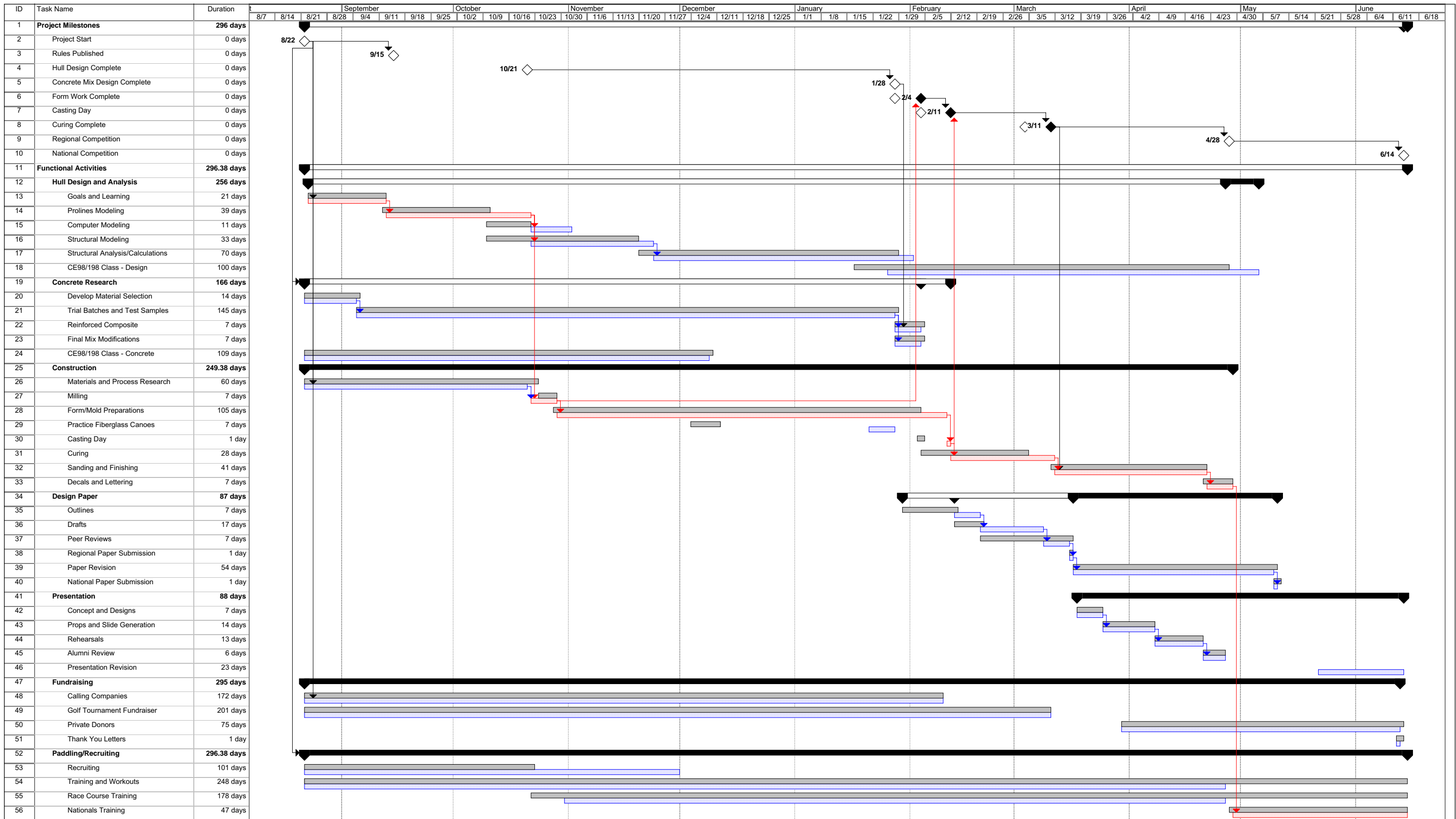
After 28 days of curing, the concrete canoe was removed from its curing tent and formwork. Then, cork sheets were replaced with blue concrete inlays. While this concrete cured, sanding commenced and was continued until the team achieved a smooth surface that can only be obtained with 2000 grit sand paper. As per manufacturer’s recommendations, lettering was painted in a setting with adequate ventilation, temperature above 50°F, and humidity below 85%, and a layer of a sealant was applied to the cleaned canoe surface with a garden-variety pump. The final product is a boat not just hot, but *Caliente*.

Organizational Chart UC Berkeley



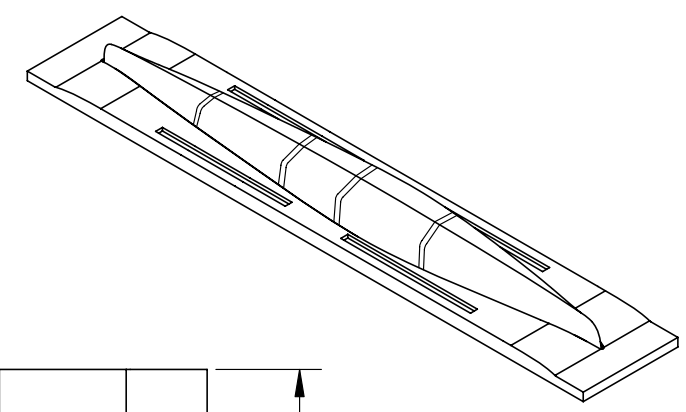
**Caliente
2005-2006**



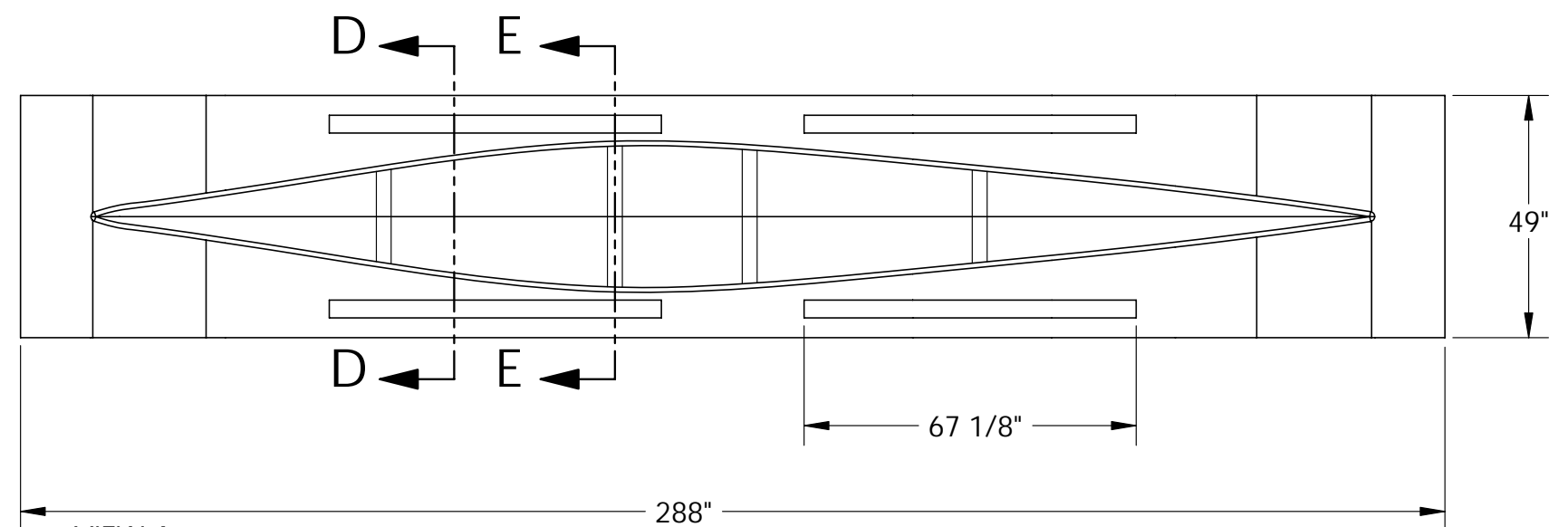


Task		Critical Task Progress		Baseline Milestone		Rolled Up Critical Task		Rolled Up Baseline		Split		Group By Summary	
Task Progress		Baseline		Summary		Rolled Up Milestone		Rolled Up Baseline Milestone		External Tasks		Deadline	
Critical Task		Milestone		Rolled Up Task		Baseline Summary		Rolled Up Progress		Project Summary			

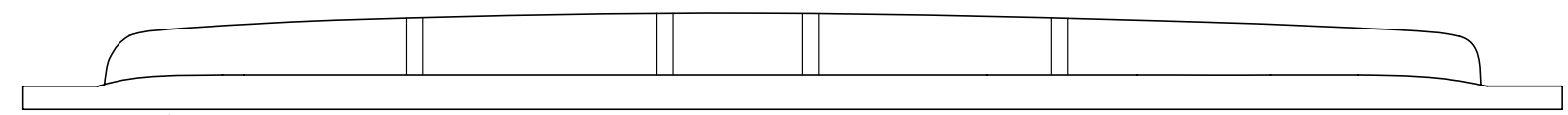
FORM & CONSTRUCTION



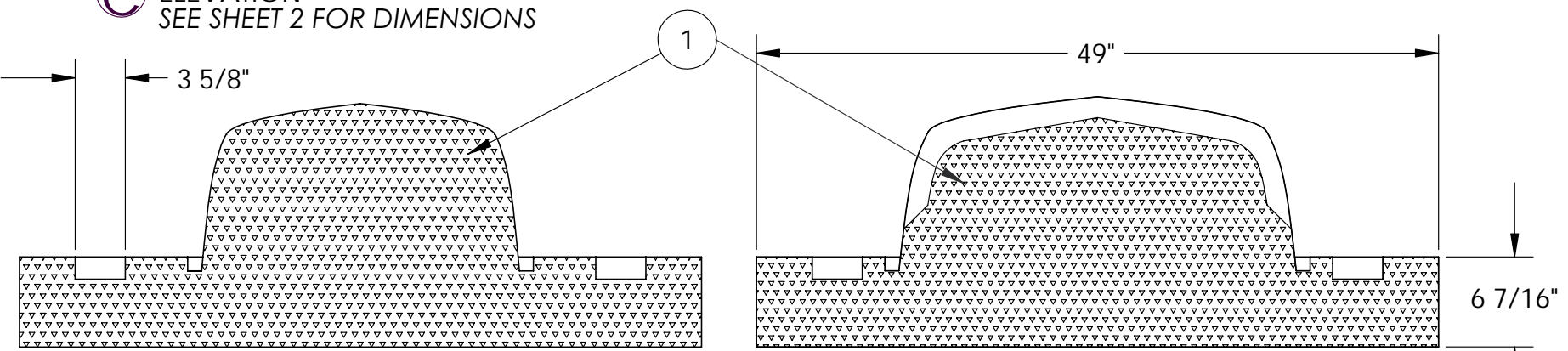
B VIEW B ISOMETRIC



A VIEW A PLAN
SEE SHEET 2 FOR DIMENSIONS



C VIEW C ELEVATION
SEE SHEET 2 FOR DIMENSIONS



D SECTION D-D
SEE SHEET 2 FOR DIMENSIONS

E SECTION E-E
(CONTAINS A RIB)
SEE SHEET 2 FOR DIMENSIONS

BILL OF MATERIALS		
ITEM NO.	QTY.	DESCRIPTION
1	1	49" x 49" x 288" BLOCK EPS TYPE I - MEDIUM DENSITY FOAM
2	1 GAL	EPOXY
3	5 LB	JOINT COMPOUND
4	40 SQ FT	1/16" CORK MAT

- NOTES:
1. Mill male foam form using CNC drilling machine.
 2. Apply 2 layers of epoxy with an intermediate layer of joint compound for a smooth finish and then apply 1/16" temporary cork to form.
 3. For thickness control, use spaced 1/8" gage speaker wire and rolling pins.
 4. Drawings not to scale
 5. Tolerance: +/- 1/8"

ENGINEER: DANNY YOST, JR.
 DRAWN BY: DANNY YOST, JR. DATE: 3/17/2006
 REVISED BY: DANNY YOST, JR. DATE: 5/9/2006
 CHECKED BY: BEN HUIE DATE: 5/10/2006



TITLE:
Caliente

Report Page NO. ASCE NATIONAL CONCRETE CANOE COMPETITION
 SHEET 1 OF 2

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Appendix B ~ Blue Flame Mix Design

Mix Name: Blue Flame
Batch Size: 0.35 ft³

		Proportions as Designed		Batched Proportions		Yielded Proportions	
Cementitious Materials	Specific Gravity	Amount (lb/yd ³)	Volume (ft ³)	Amount (lb)	Volume (ft ³)	Amount (lb/yd ³)	Volume (ft ³)
1. ASTM C150 Portland Cement Type: I (white)	3.15	438.871	2.233	5.624	0.029	465.328	2.367
2. Class F Fly Ash	2.7	94.033	0.558	1.205	0.007	99.701	0.592
3. Metakaolin	2.45	94.033	0.615	1.205	0.008	99.701	0.652
Total of All Cementitious Materials		626.936	3.406	8.034	0.044	664.730	3.611
Fibers							
1. PVA fibers	1.3	5.501	0.068	0.0705	0.001	5.833	0.072
2. Polypropylene Microfibers	0.90	2.747	0.049	0.0352	0.001	2.912	0.052
Aggregates							
1. K1 Glass Bubbles Absorption, 0 % Batched Moisture Content, 0 %	0.15	58.058	6.203	0.744	0.079	61.558	6.577
2. Z-Light 3500 Absorption, 0.22 % Batched Moisture Content, 0.13 %	0.70	116.012	2.656	1.487	0.034	123.006	2.816
3. Macrolite 1430 Absorption, 0.31 % Batched Moisture Content, 0.17 %	0.80	130.994	2.624	1.679	0.034	138.891	2.782
4. Macrolite 714 Absorption, 0.30 % Batched Moisture Content, 0.19 %	0.75	260.897	5.575	3.343	0.071	276.625	5.911
Total of All Aggregates		565.961	17.058	7.253	0.219	600.080	18.086
Water							
Batched Water	1.00	308.815	4.949	3.957	0.063	327.432	5.247
Total Free Water from All Aggregates	1.00	-0.575	0.093	-0.00737	0.001	-0.610	0.098
Total Water from All Admixtures	1.00	5.775	0.093	0.074	0.001	6.123	0.098
Total Water		314.014	5.134	4.024	0.066	332.944	5.444
Admixtures							
	% Solids	Amount (fl oz/cwt)	Water in Admixture (lb/yd³)	Amount (fl oz)	Water in Admixture (lb)	Amount (fl oz/cwt)	Water in Admixture (lb/yd³)
1. Air Entrainment	10	16.804		1.350		17.817	
2. Superplasticizer	30	18.297	5.775	1.470	0.074	19.400	6.123
3. Blue Pigment	100	27.468	0	0.352	0	29.124	0
Cement-Cementitious Materials Ratio		0.70		0.70			0.7
Water-Cementitious Materials Ratio		0.50		0.50			0.5
Slump, in		0		0			0
Air Content, %		5		6.3			6.3
Density (Unit Weight), lb/ft ³		56.12		55.59			59.5
Gravimetric Air Content, %				5			
Yield, ft ³		27		0.35			27



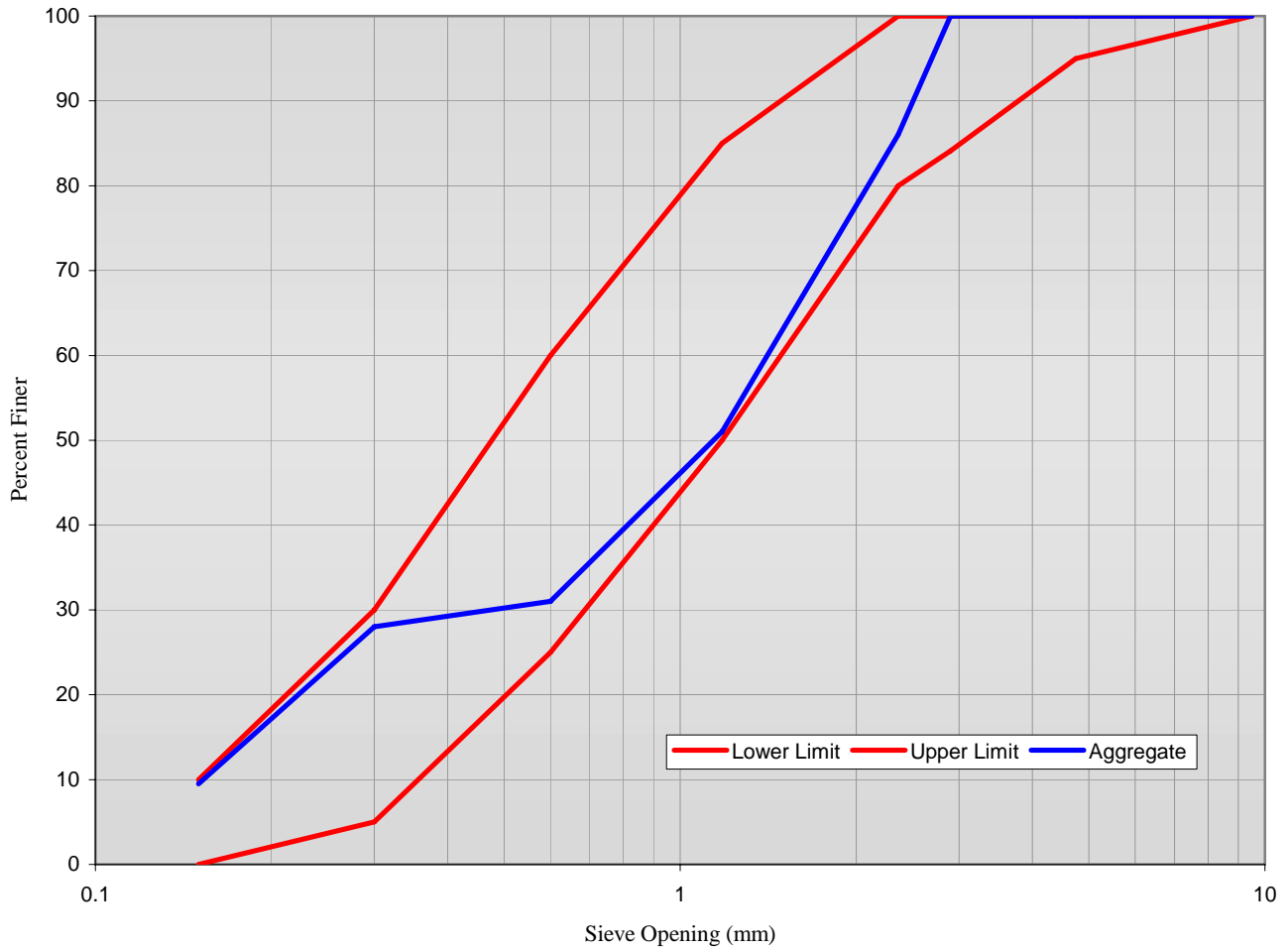
Appendix B - Pale Fire Mix Design

Mix Name: Pale Fire
Batch Size: 0.35 ft³

		Proportions as Designed		Batched Proportions		Yielded Proportions	
Cementitious Materials	Specific Gravity	Amount (lb/yd ³)	Volume (ft ³)	Amount (lb)	Volume (ft ³)	Amount (lb/yd ³)	Volume (ft ³)
1. ASTM C150 Portland Cement Type: I (white)	3.15	438.871	2.233	5.624	0.029	475.495	2.419
2. Class F Fly Ash	2.7	94.033	0.558	1.205	0.007	101.880	0.605
3. Metakaolin	2.45	94.033	0.615	1.205	0.008	101.880	0.666
Total of All Cementitious Materials		626.936	3.406	8.034	0.044	679.254	3.690
Fibers							
1. PVA fibers	1.3	5.501	0.068	0.0705	0.001	5.961	0.073
2. Polypropelyne Microfibers	0.90	2.747	0.049	0.0352	0.001	2.976	0.053
Aggregates							
1. K1 Glass Bubbles Absorption, 0 % Batched Moisture Content, 0 %	0.15	58.058	6.203	0.744	0.079	62.903	6.720
2. Z-Light 3500 Absorption, 0.22 % Batched Moisture Content, 0.13 %	0.70	116.012	2.656	1.487	0.034	125.693	2.878
3. Macrolite 1430 Absorption, 0.31 % Batched Moisture Content, 0.17 %	0.80	130.994	2.624	1.679	0.034	141.925	2.843
4. Macrolite 714 Absorption, 0.30 % Batched Moisture Content, 0.19 %	0.75	260.897	5.575	3.343	0.071	282.669	6.040
Total of All Aggregates		565.961	17.058	7.253	0.219	613.191	18.481
Water							
Batched Water	1.00	308.815	4.949	3.957	0.063	334.586	5.362
Total Free Water from All Aggregates	1.00	-0.575	0.093	-0.00737	0.001	-0.623	0.100
Total Water from All Admixtures	1.00	5.775	0.093	0.074	0.001	6.257	0.100
Total Water		314.014	5.134	4.024	0.066	340.219	5.562
Admixtures							
	% Solids	Amount (fl oz/cwt)	Water in Admixture (lb/yd ³)	Amount (fl oz)	Water in Admixture (lb)	Amount (fl oz/cwt)	Water in Admixture (lb/yd ³)
1. Air Entrainment	10	16.804		1.350		18.206	
2. Superplasticizer	30	18.297	5.775	1.470	0.074	19.824	6.257
3. Blue Pigment	100	0	0	0	0	0	0
Cement-Cementitious Materials Ratio		0.70		0.70			0.7
Water-Cementitious Materials Ratio		0.50		0.50			0.5
Slump, in		0		0			0
Air Content, %		5		6.1			6.1
Density (Unit Weight), lb/ft ³		56.12		56.12			60.8
Gravimetric Air Content, %				5			
Yield, ft ³		27		0.35			27



Appendix C - Composite Aggregate Gradation Curve



Appendix C - Composite Aggregate Gradation Table

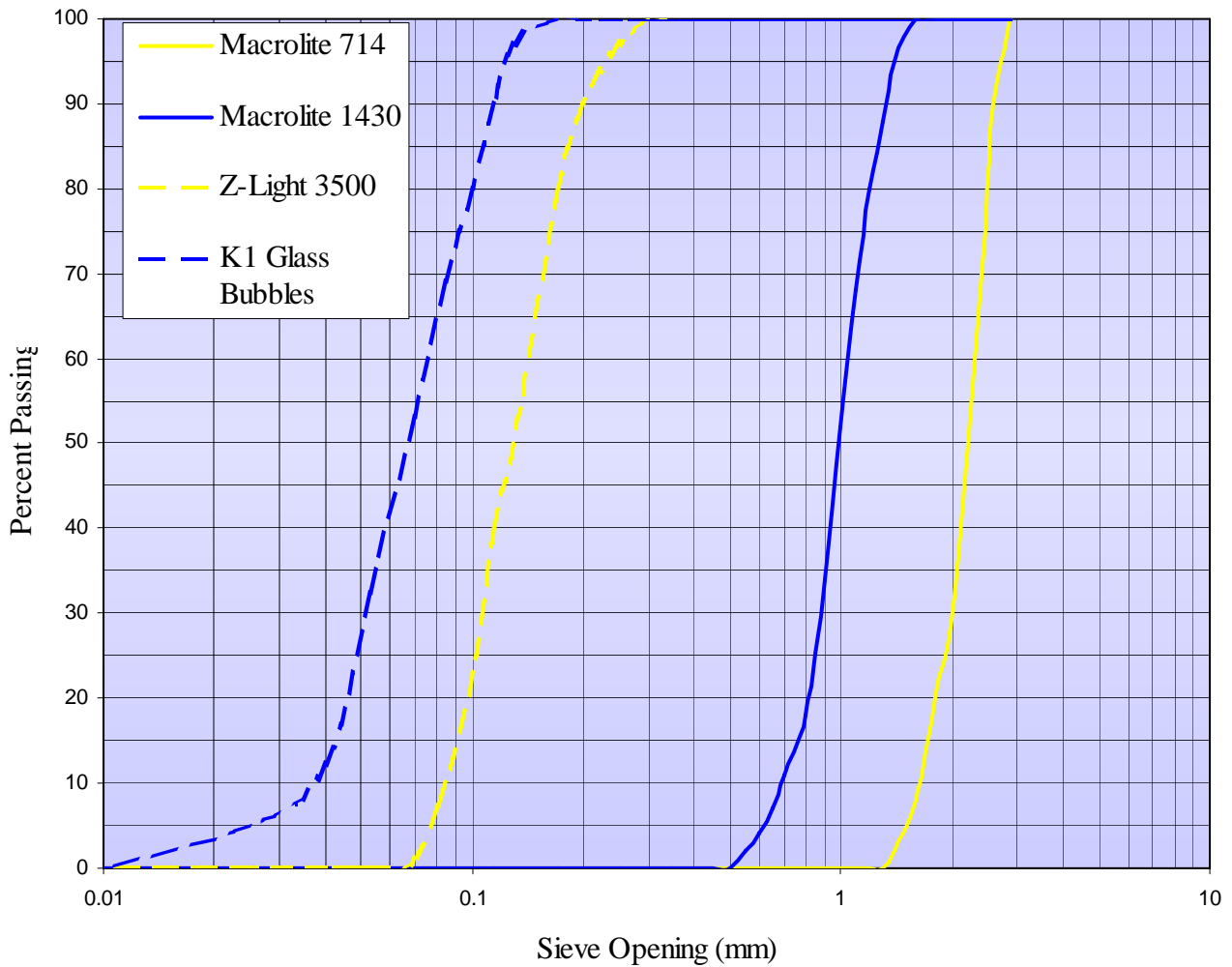
Composite Aggregate Table
 Concrete Aggregate: Composite
 Sample Weight: 100 g
 Specific Gravity: 0.69
 Fineness Modulus: 2.94

Composition:
 10:20:25:45 → K1 Glass Bubbles : Z-Light 3500 : Macrolite 1430 : Macrolite 714

Sieve	Diameter (mm)	Weight Retained (g)	Cumulative Weight Retained (g)	Percent Finer (%)
3/8 in	9.50	0	0	100
No. 4	4.75	0	0	100
No. 8	2.36	14.14	14.14	85.86
No. 16	1.18	35.86	50.00	50.00
No. 30	0.60	19.50	69.50	30.50
No. 50	0.30	0.50	70.00	30.00
No. 100	0.15	20.50	90.50	9.50



Appendix C ~ Individual Aggregate Gradation Curves



Appendix C ~ Individual Aggregate Gradation Tables

Concrete Aggregate: K1 Glass Bubbles
 Sample Weight: 100 g
 Specific Gravity: 0.15
 Fineness Modulus: 0.054

Sieve	Diameter (mm)	Weight Retained (g)	Cumulative Weight Retained (g)	Percent Finer (%)
3/8 in	9.50	0	0	100
No. 4	4.75	0	0	100
No. 8	2.36	0	0	100
No. 16	1.18	0	0	100
No. 30	0.60	0	0	100
No. 50	0.30	0	0	100
No. 100	0.15	5.4	5.4	94.6



Concrete Aggregate: Z-Light 3500
Sample Weight: 100 g
Specific Gravity: 0.70
Fineness Modulus: 1.00

Sieve	Diameter (mm)	Weight Retained (g)	Cumulative Weight Retained (g)	Percent Finer (%)
3/8 in	9.50	0	0	100
No. 4	4.75	0	0	100
No. 8	2.36	0	0	100
No. 16	1.18	0	0	100
No. 30	0.60	0	0	100
No. 50	0.30	0	0	100
No. 100	0.15	100.0	100.0	0

Concrete Aggregate: Macrolite 1430
Sample Weight: 100 g
Specific Gravity: 0.80
Fineness Modulus: 3.18

Sieve	Diameter (mm)	Weight Retained (g)	Cumulative Weight Retained (g)	Percent Finer (%)
3/8 in	9.50	0	0	100
No. 4	4.75	0	0	100
No. 8	2.36	0	0	100
No. 16	1.18	19.8	19.8	80.2
No. 30	0.60	78.1	97.9	2.1
No. 50	0.30	2.1	100.0	0
No. 100	0.15	0	100.0	0

Concrete Aggregate: Macrolite 714
Sample Weight: 100 g
Specific Gravity: 0.75
Fineness Modulus: 4.310

Sieve	Diameter (mm)	Weight Retained (g)	Cumulative Weight Retained (g)	Percent Finer (%)
3/8 in	9.50	0	0	100
No. 4	4.75	0	0	100
No. 8	2.36	31.4	31.4	68.6
No. 16	1.18	68.6	100.0	0
No. 30	0.60	0	100.0	0
No. 50	0.30	0	100.0	0
No. 100	0.15	0	100.0	0