# 1 Executive Summary/Introduction

**"Failure is only the opportunity to begin again--more intelligently."**
**-- Henry Ford.**

In 1908, Ford introduced the Model T and that year Ford sold 18,000 cars for $850 each. In October, 1913, Henry Ford revolutionized modern day production with his moving assembly line. By 1915, the Model T cost only $290 and required a mere 2 man hours to construct. Ford sold over a million cars in 1915.

For more than 30 years, engineering students have been casting canoes by hand using either a male or female form. In August of 1999, the Oklahoma State University Concrete Canoe Team--***Grand Slam***--decided to make the first injection-molded concrete canoe. By February, 2000, they had failed--twice. The ***Grand Slam*** team returned to hand casting, spent more than 300 hours sanding, and finished second at Nationals in Colorado. Last August, these students began again--more intelligently.

After two years of research, design, and construction, the Oklahoma State Concrete Canoe team introduces its injection-molded concrete canoe--***REVOLUTION***. ***REVOLUTION*** is 21.5 ft long, 12 in. deep, 29 in. wide, and weighs 140 lbs. The 28pcf latex modified concrete is injected between two layers of Carbon fiber mesh, which provides a rigid yet durable hull without the use of ribs or thwarts. The 0.75-in. thick hull is painted metallic gray with orange, black and white letters and decals. Due to the injection molding process, the ***REVOLUTION*** required only 30 hours of sanding. Oklahoma State earned its tenth trip to Nationals by winning the Mid-Continent Conference Concrete Canoe Competition.

Oklahoma State University is located in Stillwater, a northcentral Oklahoma community positioned between Oklahoma City and Tulsa. The University was founded on December 25, 1890, as Oklahoma A&M College. When the first students assembled, there were no classrooms, no books, and no curricula. In the past 111 years OSU has grown to include an enrollment of 26,000 with branch campuses in Oklahoma City, Tulsa, and Okmulgee. The 2001 Concrete Canoe team adheres to the tradition of continuing to develop and grow.

# 2 Hull Design

## 2.1 Goals

The races developed by the National Concrete Canoe Committee require the hull be designed to satisfy conflicting objectives such as straight-line tracking and turning maneuverability. ***REVOLUTION*** meets this challenge with shallow elliptical cross sections and a long slender hull.

In the past three years the Hull Design Team has made steady improvement in race performance. Yet, the coed race has been weak in 1999 and 2000 due to minor design defects.

The primary goal for ***REVOLUTION*** was improved performance in the coed race, without sacrificing speed in the other four races. Improving maneuverability, increasing paddling efficiency, and maintaining stability were secondary goals.

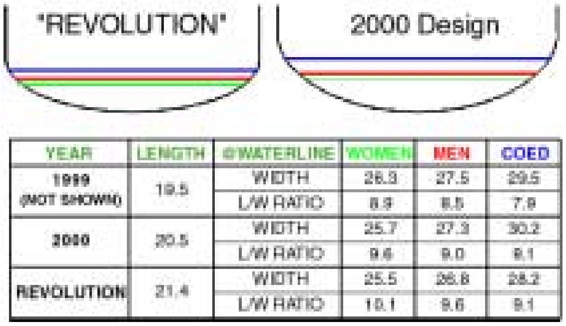
## 2.2 Design Changes

The Hull Design Team utilized the power of experience and an in-depth literature review to isolate several key variables: length, width, cross-section shape, longitudinal shape, and rocker. The key to obtaining a successful design is minimizing the total drag force (TDF).

$$\text{TDF} = \text{Skin Drag} + \text{Wave Drag}$$

Skin drag is linearly related to the wetted area of the hull. By reducing the wetted area, the skin drag can be significantly reduced. Wave drag represents the force required for a displacement hull to separate and return water around the hull. Increasing the length-to-width ratio will decrease the wave drag.

To meet its primary goal, the hull design team looked at the length to width ratios for the men's, women's, and coed loading of the past two years. In 1999 and 2000, the teams used cross sections with wide deep ellipses and sharp diamond-shaped hulls. During the coed race the boat sat much deeper in water and the width at the waterline increased significantly. The design team concluded that using shallow ellipses and a fuller hull would result in a smaller change in waterline depth and width for the various loadings. Figure 1 illustrates the effect of the design changes.



| YEAR | LENGTH | @WATERLINE | WOMEN | MEN | COED |
|---|---|---|---|---|---|
| 1999 (NOT SHOWN) | 19.5 | WIDTH | 26.3 | 27.5 | 29.5 |
| | | L/W RATIO | 8.9 | 8.5 | 7.9 |
| 2000 | 20.5 | WIDTH | 25.7 | 27.3 | 30.2 |
| | | L/W RATIO | 9.6 | 9.0 | 8.1 |
| REVOLUTION | 21.4 | WIDTH | 25.5 | 26.8 | 28.2 |
| | | L/W RATIO | 10.1 | 9.6 | 9.1 |

Figure 1 – Length to Width at Waterlines

The secondary goals of improved paddling efficiency and maneuverability were also met. The shallow ellipses and fuller hull caused the canoe to sit higher in the water, which greatly improves turning ability. The decrease in overall width and straight sides allows the middle coed paddlers easier access to the water.

This design slightly increases the wetted perimeter. However, by increasing the length-to-width ratio, the TDF was reduced.

### 2.3 Prototype Evaluation

As a part of the mold construction discussed in section 4, a fiberglass practice canoe was constructed. This canoe gave potential paddlers an opportunity to test the hull design.

As predicted, the hull design changes improved performance in the coed race and increased maneuverability through the slalom section of the distance race. Paddlers noted a slight decrease in stability and tracking, but the increase in overall length-to-width ratio improved the canoe's speed.

## 3 Structural Design

### 3.1 Concrete Target Properties

While the Hull Design team performed its analysis to optimize the hull's hydraulic performance, the Structural Design team had to respond to the demands of the four paddlers in the coed sprint. An Excel spreadsheet was programmed to use imported 3-D points from AutoCAD to compute incremental water displacements of ***REVOLUTION***. Canoe weight and four paddler weights were placed in the computer model and the spreadsheet computed incremental buoyancy, shear, and moment forces every 6 in.

As shown in Figure 2, forces generated outside the paddler locations were small and were not analyzed. All other sections were analyzed. Two conservative assumptions were made during the analysis: concrete carries no tension and reinforcement carries no compression.

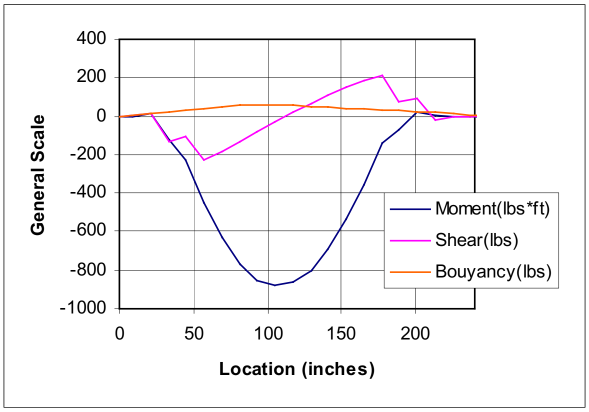


Figure 2 – Loading on Canoe Hull

The computed concrete compressive strength required was 0.52 MPa (76 psi). This was multiplied by a dynamic load factor of 2.0 and a factor of safety of 1.5 to give a final compressive strength required of 1.6 MPa (228 psi). The total tensile force required was 5.3 kN (1.19 kips).

Designing a concrete mixture that could be injected between a male and female form called for certain special target properties. The concrete needed to be fluid enough to inject without having too much excess water. It was determined that excess water could cause shrinkage, segregation, and high absorption when rewetted.

### 3.2 Concrete Material Selection

The design team broke the material selection into three categories: binders, aggregates, and admixtures. The design team settled on two binding materials, three aggregates, and one high-range water reducer.

The binders selected were portland cement and Laticrete$^{®}$ 333. The team looked at Type I and III cements and decided to use Type I due to its longer set time, which would be helpful during casting.

Laticrete® 333 is a superflexible thin set mortar latex additive that is 26% solids by weight. Latex enhances many of the desired properties of concrete canoe mixes including workability and durability, and reduces absorption and unit weight. The design team selected a latex that was suitable for exterior use, since many latexes are water soluble even after curing.

The aggregates selected include Eccospheres®, Microlite-T®, and EP300®. The Eccospheres® are silica glass hollow spheres that are 100% passing a #200 sieve. With a true particle density of only 0.227g/cc, they produce tiny, uniform, reinforced, air voids.

Microlite-T® is an expanded volcanic mineral with a specific gravity of 0.41. While 90% of this material still passes a #30 sieve, it is much coarser than the microspheres. It gave the paste portion of the mix much more body and was eliminated due to its poor performance during injection tests.

EP300® is an epoxy-coated polystyrene bead with true particle density of only 0.19 g/cc, and a nominal compressive strength of 300psi. The use of this innovative aggregate is explained in section 3.5.

Reducing the w/c ratio is an effective way to increase compressive strength and decrease absorption/shrinkage. Rheobuild® 2000B was the superplasticizer chosen to reduce the w/c ratio.

### 3.3 Compression Testing

Over 100 material combinations were tested to determine which mix constituents could be used to best meet the goals of the concrete mixture design. The wet unit weights of these mixes varied from 356 kg/m$^3$ (22.2 pcf) to 947 kg/m$^3$ (59.1 pcf). The amount of cement in each trial mixture design represented 75 to 100% of the binding material, with latex replacing the cement.

Six 2-in. cubes were cast from each 900-gram trial batch. The cubes were used to test unit weight, absorption, and compressive strength. Compression tests were done in accordance with ASTM C 39, section 7.5. A loading rate between 0.14 and 0.34 MPa/s (20 and 50 psi/s) was maintained until yielding. At yielding, no loading adjustments were made. As specimens yielded and failed, length of yield plateau and subsequent residual strength were noted. All concrete mixtures containing latex had significantly longer yield plateaus and higher residual strengths than those mixtures without latex.

### 3.4 Absorption Considerations

The unpainted section requires the final mix design to have low absorption when rewetted. The structural design team realized that even under the worse situation the canoe would only be in the water for 15 minutes at a time, and designed a mix that would have a low initial absorption. As shown in Figure 3, using a latex modified concrete and reducing the w/c ratio minimized initial absorption.

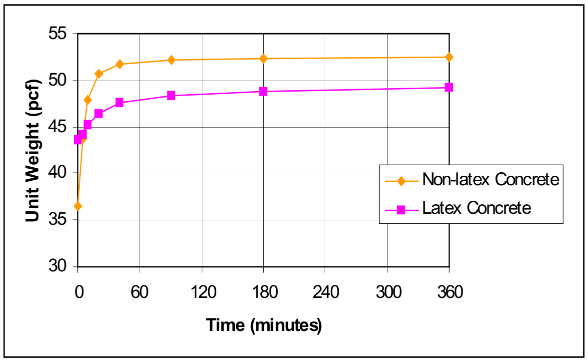


Figure 3 – Unit Weight vs. Time for Absorption

### 3.5 Flotation/Injection Considerations

The design team needed to minimize unit weight, segregation, w/c ratio, shrinkage and absorption, and still provide adequate fluidity for injection. The difficulty of meeting all these objectives with one concrete mixture is the primary reason why injection molding is so difficult.

To minimize segregation, w/c ratio, shrinkage, and absorption, water in the mix must be reduced. However, decreasing the unit weight requires the addition of tiny lightweight spheres. While these spheres do not actually soak up water, collectively they have an immense surface area that must be wetted. Additionally, producing an injectable mix requires even more water.

As shown in Figure 4, the design team discovered that by using a large aggregate in combination with the smaller aggregate, the overall unit weight of the concrete mixture could be significantly reduced. Since one 0.25-in. sphere will hold approximately 50,000 of the 0.001-in. spheres, the water demand of the concrete mix is significantly reduced.

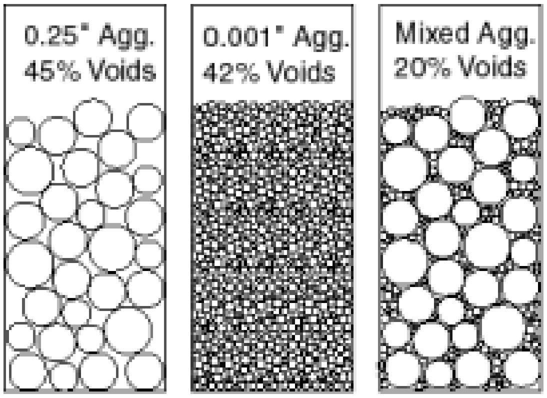


Figure 4 – Aggregates in Combination

By maximizing the amount of EP300, the design team was able to make a mix with a dry unit weight of 18pcf while maintaining a compressive strength of 250psi. However, when a full-scale injection test was done, the injection tubes got clogged. The design team reduced the amount of EP300 35% in the final ***REVOLUTION*** mix. Final mix proportions, strengths, and unit weights are shown in Figure 5.

### 3.6 Reinforcement Target Properties

The reinforcement design is perhaps the most difficult aspect of concrete canoe design. The design team was required to address the problems of point loads, hull rigidity, composite durability, and constructability.

An acceptable reinforced concrete canoe design must be able to carry shear and moment forces along the hull length in addition to redistributing bearing forces induced at paddler locations. The analysis discussed in section 3.1 generated a required tensile force along the gunwale of 5.3 kN (1.19 kips) to carry moment forces.

| Mix Name | 2000 Mix | | | Patch Mix | | | Revolution Mix | | |
|---|---|---|---|---|---|---|---|---|---|
| Binding Materials | kg/m³ | pcy | %BM | kg/m³ | pcy | %BM | kg/m³ | pcy | %BM |
| Portland Cement | 374 | 632 | 83.8 | 375 | 632 | 81.2 | 221 | 373 | 83.3 |
| Silica Fume | 0 | 0 | 0.0 | 0 | 0 | 0.0 | 0 | 0 | 0.0 |
| Fly Ash | 0 | 0 | 0.0 | 0 | 0 | 0.0 | 0 | 0 | 0.0 |
| Laticrete 333 | 73 | 122 | 16.2 | 87 | 147 | 18.8 | 44 | 75 | 16.7 |
| Aggregates | kg/m³ | | lbs./yd³ | kg/m³ | | lbs./yd³ | kg/m³ | | lbs./yd³ |
| Eccospheres | 66 | | 111 | 75 | | 126 | 66 | | 112 |
| Microlite | 42 | | 71 | 0 | | 0 | 44 | | 75 |
| EP300 | 0 | | 0 | 0 | | 0 | 0 | | 0 |
| Admixtures | | | | | | | | | |
| Superplasticizer | 0 | | 0 | 0 | | 0 | 2.7 | | 4.5 |
| Water | 292 | | 493 | 344 | | 580 | 266 | | 448 |
| Properties | | | | | | | | | |
| 7 Day Strength | 6.07MPA | | 880psi | 7.41MPa | | 1075psi | 2.10MPa | | 305psi |
| Wet Unit Weight | 847kg/m³ | | 52.9pcf | 880kg/m³ | | 55.0pcf | 645kg/m³ | | 40.3pcf |

Figure 5 – Trial Mixtures and Final Concrete Mixture

To carry the paddler point loads and the transverse deflections, the design team took advantage of the 0.75-in. thick hull. By placing a layer of reinforcement on the inside and outside of the hull the reinforcement could take the tension in either positive or negative bending. Thickness of the canoe increased overall stiffness of the hull and distributed the paddler point loads over a larger area. This stiffness also reduced transverse deflections.

### 3.7 Material Selection

The design team found numerous promising reinforcements including steel hardware cloth, and carbon fiber (CF), Kevlar®, and fiberglass meshes. Random CF and polypropylene fibers were also considered in this phase, but were eliminated due to their high degree of unpredictability when used as a primary structural reinforcement.

Steel hardware cloth was eliminated due to the difficultly of uniformly placing two layers between male and female portions of the form. While manufacturer's data on Kevlar® were impressive, no distributor was willing to donate enough material to test. The design team elected to test one fiberglass mesh and one CF mesh.

### 3.8 Raw Material Testing

The first step in assessing the final reinforcement was a standard tension test to determine raw material strength. In a standard grab test, textiles typically fail at the connection with the loading apparatus. The design team developed a loading apparatus that would reduce this tendency by rolling 1-in. strips of reinforcement on 3/4-in. diameter rods that were then pinned in place. The first and last 11-in. of each 24-in. test strip were taped, leaving a 2-in. test band. Failures typically occurred in the 2-in. test band. Figure 6 displays each of the materials tested, their specifications, and their tested strengths.

### 3.9 Composite Action/Plate Testing

In previous years, the design team elected to use a flexible composite. This "bend-but-don't-break" philosophy required the use of deep structural ribs to maintain hull rigidity. Plate testing was used to compare ***REVOLUTION***'s thicker composite section to determine if rigidity could be

| | **20 x 10 Fiberglass** | | |
|---|---|---|---|
| | | **Breaking Strength** | |
| | **Direction** | Tested | Data Sheet |
| | Warp (20) | 85 lbs. | 95 lbs. |
| | Fill (10) | 95 lbs. | 90 lbs. |
| | Thickness | .0057 in | .0052 in |

| | **8 x 8 Carbon Fiber** | | |
|---|---|---|---|
| | | **Breaking Strength** | |
| | **Direction** | Tested | Data Sheet |
| | Warp (8) | 240 lbs. | N/A |
| | Fill (8) | 200 lbs. | N/A |
| | Thickness | .0126 in | N/A |

Figure 6 – Raw Material Test Data

achieved without using any transverse structural elements. Figure 7 shows the load vs. deflection graph for plates of various thickness and reinforcement.

Plate A had a thickness of 0.25 in. and contained 8 layers of uniformly-spaced 20 x 10 fiberglass mesh, similar to the 2000 reinforcement design. This plate had the highest deflection vs. load of the plates shown. Plate B went through a period of high deflection until failure at a constant load of 38.6 lbs.

Plate B, constructed with one layer of CF on the compression face and one on the tension face, spaced 0.25 in., was rigid compared to the fiberglass plate. Unlike the previous plate, this plate failed abruptly at a load of 41.0 lbs.

Plate C also contained two layers of CF, except they were spaced 0.75 in. This plate was much more rigid and failed abruptly at a load of 130 lbs. Plate C, was chosen as the final reinforcement scheme used in ***REVOLUTION***.

## 4 Construction

### 4.1 Mold Construction

Construction of the male mold began with full-scale templates of hull cross sections. These cross sections were cut from 16-gage steel sheets with a computer-driven plasma cutter at 22.86 cm (9 in.) intervals along the 6.5 m (21.4 ft) hull length.

A 9-in. block of polystyrene then was “sandwiched” between two steel templates and a special hotwire was used to cut the polystyrene along the templates. Individual polystyrene cross sections were connected to form three larger segments. These segments were then placed on a specially designed table that would support the segments during casting/curing and allow removal of the mold. Included in the table and polystyrene mold was a dual keyway to ensure proper alignment of each mold segment on the table.

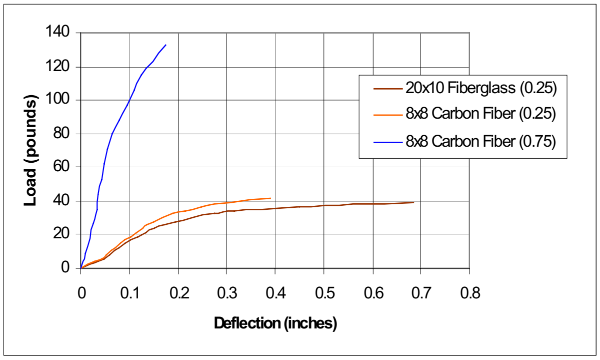


Figure 7 – Load vs. Deflection Graph

Casting an injection molded canoe requires a male and female form with a uniform space between. Creating the uniform space was accomplished by constructing a practice canoe on the male form the exact proposed thickness of the actually canoe. This was done using fiberglass and 0.625 in. thick polystyrene strips.

Once the practice canoe was completed, laying three layers of fiberglass and resin over the practice canoe made the female cap. The entire mold was taken apart shortly after the resin had cured. This left the team with a male mold, a female cap, and a perfect fiberglass practice canoe.

### 4.2 Concrete Canoe Construction

Prior to casting, both reinforcement layers were placed between the male mold and female cap. Three 2-in. diameter, 20-ft long flexible hoses were placed between the layers of reinforcement. The form was removed from the table and flipped right side up for casting. All mix constituents were premeasured for easy mixing.

Casting of the canoe began by filling the tubes with mixed concrete and attaching the bottom hose to the injection tube. As the canoe was injected the injection tube and hose were pulled away from the mold. Once the first tube was removed, the second hose was attached and the injecting process was repeated. The canoe was filled from stern to bow.

After one week the female cap was removed and minor patching was done on the exterior of the canoe. One week later the male mold was removed. Once patching was completed the canoe was primed and painted.

The hours spent patching, sanding, and painting was reduced 90% from last year.

## 5 Project Management and Cost Assessment

### 5.1 Organizational Approach

Beginning in August, the project manager developed a Work Breakdown Structure (WBS) for the project. It included basic tasks associated with design, construction, and documentation of ***REVOLUTION***. Next, the Organizational Breakdown Structure (OBS) was adopted with each task in the WBS assigned to a committee. The OBS and assigned tasks can be found in Appendix D.

### 5.2 Project Implementation

Once the responsibilities were assigned, the work began. To attract new students and inform incoming students, a slide presentation about the 2000 OSU Concrete Canoe Team was given at the first ASCE chapter meeting of the fall semester. The following weekend an orientation meeting was held for all people interested in being part of the team. The meeting included concrete canoe paddling for new members, a trip to the concrete canoe lab, a brief description of the 2001 OSU Concrete Canoe Team goals, and a picnic provided by the faculty.

Over the next two weeks, individuals were assigned to teams based on their interest, knowledge, and experience. Team members with the most expertise were appointed committee leaders and were asked to educate new members. Teaching was the most important responsibility of committee leaders. By passing on the knowledge of past successes and failures, team leaders guarantee victory for future canoe projects.

### 5.3 Project Schedule

A detailed critical path diagram was developed in August to show the interrelationships between various tasks each committee was assigned to complete. A simplified version of the project schedule is located in Appendix D.

### 5.4 Cost Assessment

All materials used were cataloged in a project notebook kept at the concrete canoe lab. A simple time sheet that contained spaces for name, hours spent, and specific activities performed was also kept in the project notebook. These records were periodically compiled in a spreadsheet and then removed from the project notebook.

Using the labor and material rates outlined in the 2001 Rules and Regulations, the compiled records were converted to labor and material costs detailed in Appendix A. Labor costs for research/development and concrete canoe construction came to $37535.84. Material costs for research/development and concrete canoe construction totaled $3504.35.

The grand total for development and construction of the ***REVOLUTION*** was $41040.19. However, the reproduction cost for ***REVOLUTION*** was only $5934.94.

## 6.0 Summary

**"Unless you try to do something beyond what**
**you have already mastered, you will never grow."**

For 30 years, engineering students have been constructing concrete canoes by hand. More than 300 hours were spent sanding OSU's National runner-up--***Grand Slam***--in 2000. ***REVOLUTION*** required only 30 hours of sanding. The Oklahoma State Concrete Canoe Team can now produce 10 canoes in the time that it used to make one, and each canoe will cost approximately one-tenth of last year's National runner-up. Diligent research created advancements in concrete mix and reinforcement designs. A successful top-down management structure ensured the project was completed on time and under budget. The advanced injection-molding system produced the finest canoe to ever leave Stillwater, Oklahoma. The Oklahoma State University Concrete Canoe Team made a decision in August, 2000, to do something beyond what they had already mastered—they found a ***REVOLUTION.***