Independent Carts

Il Calamaro

One man, human powered,

non-propeller, wet submarine

Final Design Report for The 2013 International Submarine Races

May 2013

Dedication

To God - Author of Science

and

All the uniquely skilled and wonderful people who have helped enlighten us along the way.

Table of contents

ABSTRACT

We are a team of families from Charles County , Maryland, inspiring our students to love science , who designed and built a one man, human-powered, non-propeller submarine to compete in the 12th International Submarine Races at David Taylor Model Basin in Bethesda, Maryland in June 2013. The fiberglass, wet hull is driven by a propulsion system that employs a pair of book-like paddles that open, providing thrust when the pushrod is extended and close when the pushrod is retracted. The paddles can act in tandem or independently.

This report outlines our efforts, focusing on the scientific methods we employed and great nuggets of knowledge acquired on our journey.

Introduction

Inspiration

Paola and Sam Carts were the first to be hooked on the challenge of designing and building a human powered, wet submarine after attending a SNAME Marine Forensics conference at the Gaylord Convention Center in April 2012.

Sam sought a hands-on science experience for his junior year of homeschool high school. ISR appeared to have all the elements—it would leverage his recently acquired skills of SCUBA (having just received his SCUBA certification for Boy Scout Sea Base during the summer of 2012); would incorporate his love of bicycling; and most importantly presented a fascinating challenge.

Forming the Team

Although the pair were initially unsuccessful garnering participation in the homeschool community, there was a great deal of interest among younger students who were acquainted through swim team and church. The students were also looking for a more challenging STEM experience and—with strong parental support—four families from Charles County, Maryland and one college-level engineering student in Virginia joined together to form Il Calamaro. Together the students represent a diverse educational experience—elementary to college—home schooled, private and public school.

Carts Family
- Sam
- Paola
- Marty
- Stan

Gerstman Family
- Abby
- Ella
- Sophie
- Chad
- Jen

Schwalm Family
- Teddy
- Josie
- Steve

Individuals
- Lydia Kivrak
- Mike Campola
- Karl Larson

Project Management 101

Defining the Project

The first two months of our project we spent a great deal of time learning the basic principles of project management. Although this was a significant amount of time in our limited schedule, family members felt this was an important part of the education experience - the application of the principles will transcend and apply to any issue the students would encounter in future endeavors. We began by defining our mission and realistic goals for the team.

Mission:

To design and construct a one-man, non-propeller submarine that will successfully complete the ISR course within a modest budget.

Goals & Objectives:

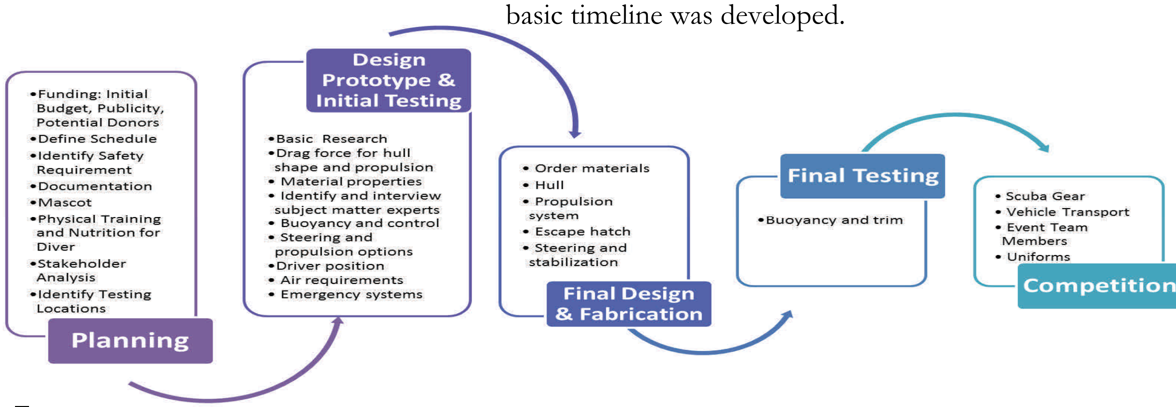
I. Successfully complete the project and cross the finish line

II. Maintain buoyancy

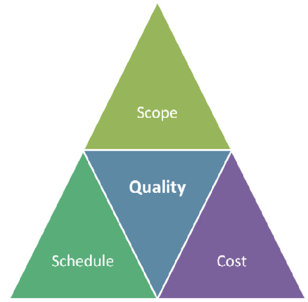
III. Gain project management, design and construction skills

IV. Recognize the contributions and knowledge of individuals we encounter on our journey and ensure we graciously acknowledge their contributions

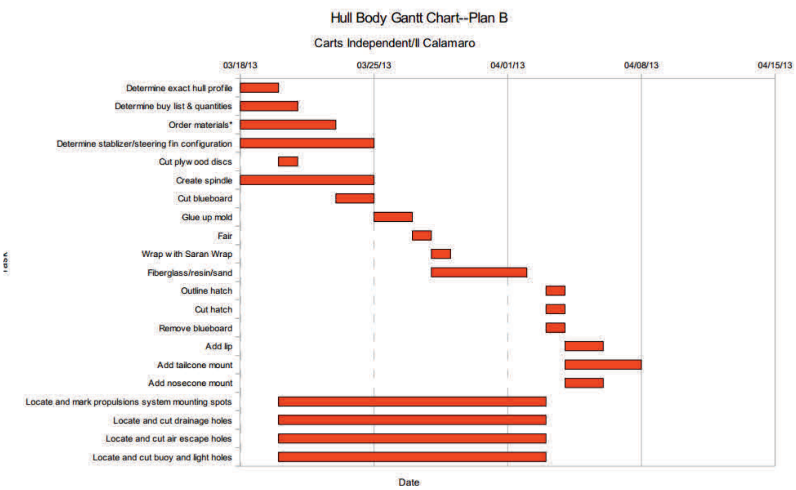
Once our mission and goals were agreed upon, we set out to define the phases of our project. Using the internet as our primary source, we researched various project models. The one that most closely fit our endeavor was the Systems Engineering Life Cycle from education.ksc.nasa.gov and formed the basis of our phases. We made minor modifications which resulted in the five phases detailed below. We then brainstormed and used sticky notes to list all the tasks which we needed to complete. Each task was posted to the appropriate phase and a basic timeline was developed.



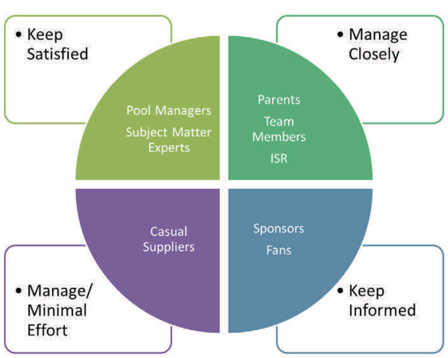
Project Troika—a.k.a. Triple Constraint



Although we discussed the basic concept behind how changes in scope, cost or schedule would affect the quality of our submarine, it wasn't until late winter when we started feeling the true impact. Cost: we had a limited time to fundraise while simultaneously focusing on research, design and construction. Essentially the budget was set by the maximum amount the families could afford without external support. The budget affected our ability to outsource components and delayed decision on material selection for fear that we would misspend our limited financial resources. Schedule: another example of an area affected by external controls—that being the set milestones for ISR competition deliverables. We established an aggressive schedule to design each of the submarine components to accommodate in significant water testing. Life schedules and impact of outside activities found us rebaselining our schedule at least three times during the late winter and spring, and limited our ability to make major adjustments once all the components were integrated. Scope: of all the three elements, scope was the one most within the team's control. Although the team had many innovative ideas, we were constrained by cost and schedule to focus on the basic elements for the 2013 competition, such as basic hull construction. In the future we would like to also include innovative navigation technology in addition to the items listed in the lessons learned sections for each of the components.

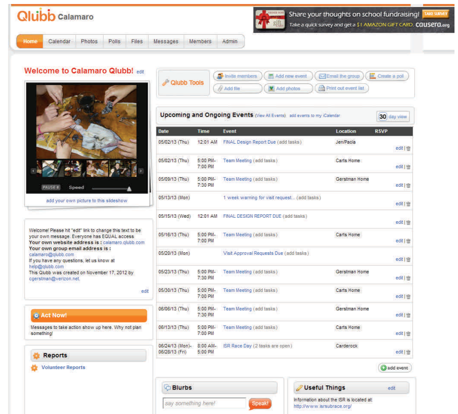


Stakeholder Analysis

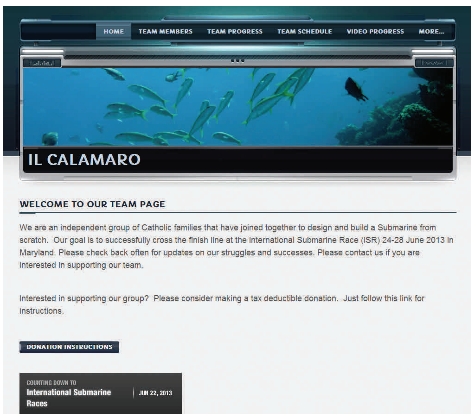


As part of defining the project, we listed all the stakeholders involved in this effort. Once we listed each stakeholder we placed them on a matrix to define their level of interest and what deliverables each would expect of the group. This analysis helped focus the group on properly documenting and communicating with each stakeholder and led to our communication plan. As much as we thought we were keeping a thorough record of our efforts, as we write this report we realize that we could have done more.

Communications Plan



After defining our various stakeholders, the team analyzed the amount and form of communication required by each stakeholder. The team decided to leverage a free, social network platform called Qlubb for internal dialogue, information sharing and scheduling. The team recognized that regular email or newsletter updates to interested parties and supporters would quickly become overwhelming, so the team leveraged another free, web-based platform—Weebly—to create a team website. Team members were able to contribute to public website to provided updates on the team progress. It also provided a donation link, and links to web-based resources the team found. Weebly administrator tools allowed us to track interest in the site. The team also created marketing materials such as introduction letters and brochures to solicit support. As of May, the Weebly site had received 672 unique visitors since creation.



Assigning Roles & Responsibilities

The group agreed that everyone would try to participate in all aspects in the submarine research and construction as their school and activity schedules allowed, but similar to any other large project the team recognized that leads were needed for each of the defined components to ensure the project stayed on track. Each student was allowed to self-nominate which area they would take the lead on , with family members filling in the gaps. Leads were responsible for scheduling meetings, identifying potential materials, and documentation.

Role	Responsibility
Hull Design (Sam)	• Design hull shape, nosecone, hatch and stabilizers. • Interface with propulsion, steering and life support • Select and detail construction method and materials.
Hull Construction (Paola/Sam)	• Develop constructin plan; acquire materials and tools • Set schedule and arrange for assistant labor • Work with other systems groups to polish systems interfaces and install systems into hull • Train crew on handling and operation
Propulsion System (Marty)	• Design propulsion system including tailcone interface • Interface design with hull • Construction propulsion system and interface with hull construction
Steering System (Abby/Teddy)	• Consult with hull design for constraints and requirements • Design steering system • Help with materials selection, acquisition, construction and interface with hull

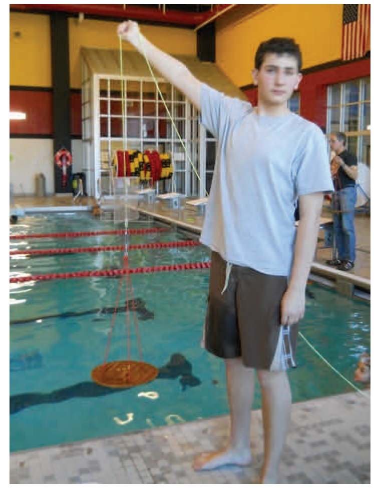
Jacques Cousteau & Company (Chad)	• Collect dive certification information for all to fulfill ISR requirements • Coordinate/recruit dive team members • Research dive equipment suppliers • Manage dive team thru testing and race week
Transport Crew (Grandpa Stan)	• Interface with hull systems • Design and construct sub cradle for holding sub during work and transporting sub from trailer to/from water • Acquire enclosed trailer for on-site secure storage • Acquire trailer for sub and cradle
Chef (Grandpa Lee)	• Provide select meals on site
Isaac Newton (Lydia)	• Perform mathematical calculations to identify buoyancy and hull requirements
Dive Team	• Coordinate thru Jacques to provide manpower during water tests and raceweek to insert sub, trim sub, survey safety concerns and certify sub safety readiness, remove sub
All	• Contribute content to and help merge technical reports • Maintain safety culture • Attend race
Emergency System (Ella/Teddy)	• Consult and collaborate with hull design and design document regarding requirements for deadman switch. • Consolidate requirements into design document • Design emergency system and help acquire materials and build system
Life Support Systems (Chad)	• Consult and collaborate with pilot and trainers and design document to develop requirements for primary and secondary air systems • Design life support system, acquire components, assemble and interface with hull • Develop plan for life support system use
Pilots (Sam/Karl)	• Work with trainers/experts to develop and implement physical training program • Work with nutritionist to develop and implement nutrition program • Pilot and propel the submarine
Della Street: Secretary Communications (Paola)	• Track money, pay bills, detail and manage budget • Track ISR milestone requirements and ensure team compliance • Submit ISR and any other forms required • Assist with information research and cultivate contacts
Fundraising (Josie)	• Develop fundraising material • Troll for sponsors, grants, donations
Program Manager (Jen)	• Organize project timeline, rebaseline timeline as necessary, pester people • Establish on-site race week plan (logistics) • Hold people accountable and compile final report
Technical Writer/Presenter	• Establish and maintain blog and communications websites • Lead presentation team

*****

We decided after submitting the outline to present the following sections by system component, describing each phase of the project management cycle for that element. This allows the reader follow the evolution of each element without having to flip to various phases in different sections. Although initially defined as a separate phase, testing was woven into research (as we discovered new concepts we tested to see if they were really feasible), design (to check to see if we were on the right track or had to go back to the drawing board) and fabrication to ensure the final product would actually work. As such, testing is not a separate discussion, but appropriately woven through all the phases.

Foundational Research

Submarine Basics

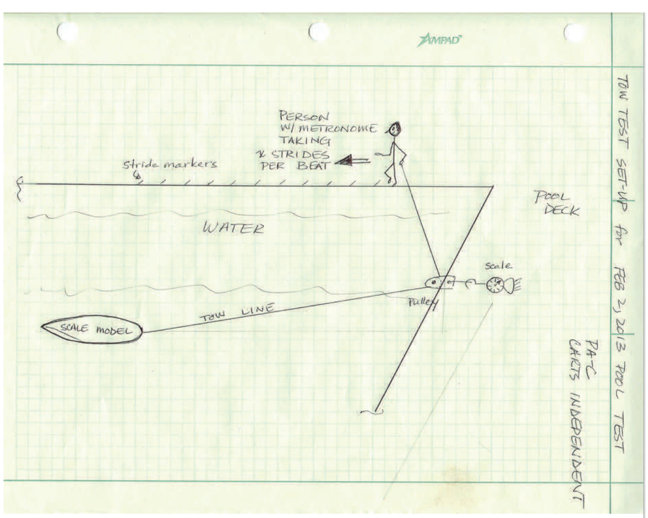


One of the first local field trips we made related to the submarine project was to visit Chesapeake Light Craft in Annapolis, Maryland. Owner John Harris said, "Design the propulsion system and everything else will follow." He also confirmed the need for a well-developed project plan. His experience in helping school teams was that projects that did not succeed had poor or no project plans.

The internet proved an invaluable tool in tracking down information about the International Submarine Races, past entries, submarine technology, manufacturing techniques, propulsion system ideas, etc.   Some articles were hard to get hold of through normal library services.   Using WorldCat.org we determined that some sources were available through the University of Maryland. Another article we particularly wanted was available at the National Oceanographic and Atmospheric Administration library where Caroline the librarian volunteered to scan and email us pdf files of the article.

We tried to contact local teams that had entered in the past. We were able to correspond with Don Burton of Frederick, Maryland, who offered this advice: "Your credit card will really be smokin' when you're done. Just the entry fees, scuba gear, rental items, and travel are just the beginning."

We saw that Old Saybrook High School was located conveniently close to the US Coast Guard Academy where a team member's sister attended college, so the Carts family arranged a field trip to visit Mr. Frederic Frese and his team's submarine, Miss Jesse II, in conjunction with a visit to USCGA. Mr. Frese lavished his knowledge and "lessons learned" on our team (and gave us a copy of the book he co-authored with Roy Manstan, *Turtle: David Bushnell's Revolutionary Vessel*). We were dazzled by the excellent craftsmanship we saw there; we were equally impressed by the cost of some of the items (hull worth over $50,000) and the networking Mr. Frese used to have things donated.



We talked to Tim Caffarella and John Harmon, team members from an early ISR entry Da Vinci II and both engineers at Raytheon. They were extremely encouraging and told us their approximate budget ($700 for their hull). We ended up talking to Mr. Caffarella several times during our journey.

Because we are Maryland-based, it was also convenient to set up a field trip to the David Taylor Model Basin so that we could observe the ISR competition facility.

Kinesiology and Human Movement

Bicycling is a passion of several team members, so we first started looking at recumbent bicycles. Members of the Oxon Hill Bicycle & Trail Club allowed us to try out their recumbents and to photo document their mechanics. We also studied recumbent bicycle cowlings. When we had a better understanding on the need for a minimal entrapped water volume—mostly gained through dinnertime conversation with our physicist neighbor—it seemed that the pilot would need to be supine or prone. The visceral reaction to being fully supine in a small, dark, enclosed space was negative. [This reaction was later confirmed by comments documented by MIT's Icarus/Sea Beaver team…]

We consulted with dance and pilates instructor Mrs. Deborah Stanley, principal of The Studio Cooperative in Waldorf, Maryland, to see what would be the best use of human movement to propel the sub. In general, she suggested that a recumbent design would be preferred because of the support of core muscles. However, as long as the pilot was in good condition, having trained for the anticipated motion required, a prone position could work.

We also initially assumed rotary foot motion. Since our propulsion system would require a linear driveshaft motion, so we researched methods of converting rotary to linear motion.

Material Properties and Costs

We realized we would have to set budget. We anticipated that the primary fabrication cost was going to be the hull. We saw that at least one early team had made a hull from salvaged cardboard and resin. We considered many materials, but narrowed down our choices to: bentwood barrel frame with fabric hull, fiberglass, thermoplastic. We researched these manufacturing methods, tools required, etc.

The Hull

Research.

Our initial concept was to build a wooden framed hull with fabric skin. We began internet research on how to construct wooden framed boats and types of fabric skins. We saw a youtube video of a high school physics project where students designed boats using 2x4s for framing and marine shrink wrap for the skin. Mr. Carts happened to mention this to an acquaintance, and before you knew it, our team was the proud owner of a donated propane-fired heat gun (mwa ha ha!) and many yards of marine shrink wrap. (Thank you, Mr. Blue!)

Simultaneously, we were learning about steambending wood, a skill that would be necessary to make the wooden frame. Mr. John Hollyfield, a local industrial arts teacher, was extremely generous with his time and talent, showing us his homemade steambending tube and offering lots of advice. One of many things Mr. Hollyfield emphasized was the need for clear drawings to assist communication and fabrication.

To practice this technique, we would need some green wood. Sam and his mom spent one day driving around to local sawmills to see what might be available. In the end, it was a business card posted in the JFK Council Knights of Columbus Hall that led us to another invaluable resource: Mr. Greg Ferris.

Mr. Ferris is a "retired" engineer who used to contract with the federal government. He put down the floor in the museum at the Navy Yard. He also was responsible for dismantling a couple of wind tunnels at the Naval Surface Warfare Center in Carderock, Maryland. He now raises bees. He sells bees, too. He makes all his own apiaries and makes most of his money selling bee boxes. He added a sawmill to his operation as a cost-saving measure for the bee box production. We toured his sawmill and workshop, and saw band saws, planes (one big, one small), a table sander, a CNC milling machine he built, a bee box joiner he built from 4 pneumatic staple guns, a bee box side router machine he built to make special cuts on his "new and improved" bee drawer sides, etc. He also has a kiln for drying lumber. He uses tailings to run the furnace that heats the air to 130F. He dries the lumber for 2 days or until the wood is 6% water content. All the insects get killed, too.

Mr. Ferris cut down a sweet gum tree for us and milled it to various thicknesses. He was very interested in our project and offered to help us. He said, "I don't want to see that boy get drowned."

He showed us the pick up truck cap that he'd improved with 1/4" plywood covered with one layer of fiberglass on each side. It was very strong. He suggested we could make a fiberglass hull. The mold would be made from dense foam that could be cut with a hot wire. If we made outline guides, we could cut the profile with the hot wire at north, south, east, west compass points, then rotate the mold 45 degrees and repeat, then rotate the mold 22.5 degrees and repeat, etc.

He told us that if we were to use the wood frame, we would need to paint and seal it. He recommended using a mix of fiberglass resin and acetone for the sealant. He uses Max CLR fiberglass resin. Fiberglass could then be put over the frame.

Thus, although focused on a steambent wood frame, the possibility of a fiberglass hull was still an option.

> *"If you don't have it [3D CAD], you have to do it the old-fashioned way."*
> *Davey Hearn*
> *Owner, Sweet Composites*

Design

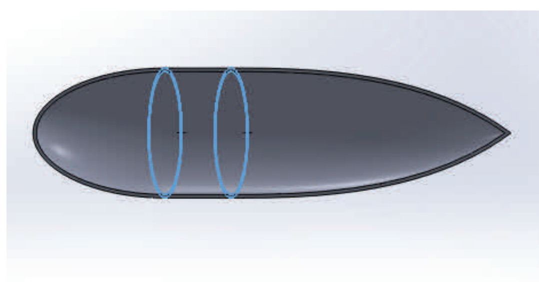
Submarine Surface Area and Volume

	Front (Ellipse)		Middle(Cylinder)		Rear (Parabola)	
Definition	The set of points for each of which the sum of the distances to two given foci is a constant.		A solid geometric figure with straight parallel sides and a circular or oval section.		The set of points equidistant from a single point (the focus) and a line (the directrix).	
Position Function	$\left(\frac{x^2}{a^2}\right)+\left(\frac{y^2}{b^2}\right)=1$		$y=h, x=r$		$y=a\cdot x^2$	
Volume Function	$\int Pi*(x^2)dy=Volume$	2898.12	$\int Pi*(x^2)dy=Volume$	977.9124	$\int Pi*(x^2)dy=Volume$	1336.757
Surface Area Function	$\int 2*Pi*x*\sqrt{(x'+1)}dy=SurfaceArea$	907.456	$\int 2*Pi*xdy=SurfaceArea$	318.0203	$\int 2*Pi*xdy=SurfaceArea$	595.9386
	Length of Ellipsoidal 15	#VALUE!	Length of Cylinder= 8.2		Length of Parabolic Section= 22.5	
(If a full half ellipse) b=	6.15		Radius of Cylinder= 6.2		A (wider>1>narrower)= 0.59	
(If a full half ellipse) a=	15					

Total Submarine Length=	45.73	# of Bulk Heads	20	Distance Between Bulkheads=	2.3	Radius of Circle for Bulkhead
Total Submarine	5212.78908		1	0		0
Total Submarine S.A.=	1821.41528		2	2.2865		3.263737
Ratio S.A. To Volume=	0.34941281		3	4.573		4.421117
			4	6.8595		5.165549
http://www.math.ucla.edu/~ronmiech/			5	9.146		5.662316
Calculus_Problems/32A/chap9/sectio			6	11.4325		5.973532
n3/564d27/564_27.html			7	13.719		6.127532
			8	16.0055		6.15
			9	18.292		6.15
			10	20.5785		6.15
			11	22.865		6.15
			12	25.1515		6.15
			13	27.438		5.545165
			14	29.7245		5.187027
			15	32.011		4.802254
			16	34.2975		4.383838
			17	36.584		3.921024
			18	38.8705		3.395706
			19	41.157		2.772582
			20	43.4435		1.960512

Our hull shape was influenced primarily by our findings in the excellent paper on hydrodynamics of submarine design written by Professor P.N. Joubert (see bibliography). From this we learned: "The ideal form involves a continuously changing diameter along its length. The bow would be ellipsoidal and the stern paraboloidal in shape." The optimal length to diameter ratio was about 6.

The propulsion system (see later section) would require a prone pilot. Thus, to determine our submarine length, bow ellipse and stern parabola, we positioned the pilot on a large sheet of paper and traced, as the stepping motions of the pilot were acted out, an outline of a potential submarine hull. We found we needed to add a cylindrical section in the area of the pilot's hips and knees to accommodate action. There would be a penalty in skin friction, but the submarine wouldn't go far if the pilot was unable to move.



We took the critical dimensions from the outline and proposed several configurations that utilized the ellipsoidal bow/paraboloidal stern ideal, all with a cylindrical midsection. We settled on one that accommodated the pilot and all the internal hardware, but had minimal entrapped water volume. This included a front section, 30 inches in length, that formed an ellipse; a central cylindrical section, 15 inches long; and a trailing edge, a truncated parabola, for a total submarine length of 9' 6".

It was time to create a half-scale model. The model was created by making a bentwood frame using sweet gum stringers and plywood bulkheads. Black walnut, harvested from a tree fallen in a team member's backyard, was turned to create nose and tail cones. Everything was sealed with deck sealer. Assembling

the wooden framework was trickier than we thought, as lining up the bulkheads so they were concentric and parallel was no easy task. We ended up developing a number of jigs to hold everything in place while we screwed the components together.

We took this simple frame to the pool, wrapped it with cling wrap, and conducted initial trim and buoyancy tests. After observing how the model behaved, we added PVC ballast ports before applying a more robust skin.

Next, we screwed eye bolts into the nose and tale cones so that the frame could be suspended while the marine shrink wrap skin was applied. Working with the propane-fire heat gun was fun. It makes a lot of noise. We had limited amounts of marine shrink wrap, so we carefully tested to see how it would shrink and how it would adhere to itself. After a couple of attempts, we have a workable layer of shrink wrap on the frame. We took this model to the pool and fairly quickly realized our ballast system was inadequate….the weights ended up rolling around the bottom of the sub. This was one lesson learned that we would carry over to the final sub.

We attempted to conduct tow testing on this model to see what drag force we would have to overcome. The model kept breaching the surface, and we were unable to obtain much useful data. Subsequently, we talked to several engineers who were used to conducting tow testing. They recommended a number of changes (adding torpedo diver to line in front of model, submerging pulley to depth of model). We tried all these changes with somewhat better results and were confident that our hull configuration would be suitable for the propulsion system.

We began hand drafting our final drawings for the full size submarine using a bentwood frame. When reviewing the drawings, we felt, based on our limited experience with wood framing a hull, that the framing necessary for this technique would intrude too much into the pilot compartment. It was at this point that we decided to use fiberglass as our hull material.

Fiberglass: We had continued to interview subject matter experts to ensure our theories were sound. We contacted a local marine fiberglass construction/repair business owned by Ray Rye. Mr. Rye suggested making a mold. His consulting fees were cost prohibitive, likely due to a bad experience he'd had collecting fees from a local university's solar car team. We then contacted Senior Technical Engineer Russ Elkins from 3A Composites. Mr. Elkins suggested using a one-off core construction technique and sent us an excellent book on the subject. We also initiated an email correspondence with Gurit USA technical sales. They recommended fiberglass with no core. Then we talked to Greg Ferris, remembering he had volunteered to help us with our project. He suggested building a blue board (= extruded polystyrene) plug, building up the plug from pieces cut on his CNC machine. The only problem was that he needed us to give him files in G Code for cutting the blue board. This would require us to generate an assembly using 3D CAD, a skill none of us had. We found a freelance 3D CAD draftsman willing to do the work, but just when we were ready to hand the work off to him, he was required to travel for his engineering job. Simultaneously, in looking for a local fiberglass supplier, we discovered Sweet Composites. We spoke with owner Davey Hearn on the phone and he was very helpful. Mr. Hearn is a former US Olympic whitewater canoe/kayak racer. Every boat he's ever raced in, he's built himself. He gave us many ideas and told us how to construct a plug the "old-fashioned" way, by cutting circles and stacking them like pennies. Due to time constraints and limited options, we decided to follow Mr. Hearn's advice. Other advice Mr. Hearn gave us included:

> **Materials**: 10 ounce fabric is the workhorse of fiberglass—it's heavy but still easy to use. Although the West System website provides guidelines for how much epoxy resin to use, Mr. Hearn made some quick calculations and said we should use 55% resin for 10 ounce fabric. He said that a boat with 1/8 inch thick skin is fairly stiff and that should be fine for our sub. That equates to 4 to 6 layers of 10 ounce cloth. He said we should err on the side of less because we can always add more layers, provided we haven't painted it.

Mr. Hearn confirmed that blue board (extruded polystyrene) would work for plug material, but he suggested we might consider bead foam (expanded polystyrene) because it is easier to dig out. He has used three inch bead foam cut in circle on a band saw—cut out paper circles, glued to foam and then cut on the band saw. Mr. Hearn said using a spindle to shape the plug would be fine. He used a light to project a shadow on a wall to line up his plug. He did note that we would need to lock the spindle because it would be no fun trying to lay fiberglass down on a moving object. Drywall mud could be used to smooth out any bits or chunks of foam that break off while fairing.

Laying the Fiberglass: We should only work on one-third of the circumference at a time, masking off the sections not being worked—to prevent the resin from dripping down. Mr. Hearn said that we could do all four layers, tapering the overlay area, possibly filing the layers to tapered edge so we wouldn't have ridges. He reminded us that the shop needs to be above 50 degrees Fahrenheit for the resin to set properly—although 65 to 70 degrees Fahrenheit is optimal. Given our experience level, we used the slow hardener. Given that our OD is 28 inches and one-third of the circumference is about 29 inches—he said the 60 inch wide fabric would work well, and we could cut it in half to get two layers for the exposed working section. He suggested we might add more layers in the mid-section where the pilot is situated, but might not need to since our shape is pretty rugged. He also agreed that adding windows to the nosecone makes more economical sense.

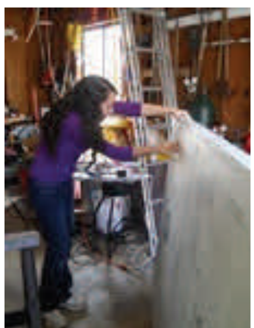
Fabrication

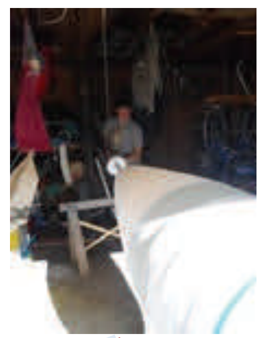
Our next objective was actually obtaining some polystyrene insulation, otherwise known as "blue board". First we went to Lowe's, but they only could sell us blue board in the size we wanted it in cases of 32 sheets minimum. After talking to several stores and contractors we knew, we found an 84 Lumber branch which had the polystyrene in stock. Earlier we had contacted a "friend of a friend", one Mr. Jerry Walls, who turned out to be on vacation when we first talked to him. We gave him dimensions of the sheets we wanted. Then he said he would call us back if he got anywhere. After a few days we assumed he couldn't get the polystyrene after all. We decided to head to 84 Lumber where we purchased what we needed and headed home. The next day, we were building the first circles when we got a call from Mr. Walls who had not only gotten back from vacation, but had custom-ordered the polystyrene from Mid-Atlantic Foam, and was on his was to our construction site to drop it off! In the end, we used all of it and had some extra. A good mistake.

Now that we had the polystyrene insulation, and were prepared to make the circles, it was almost time to begin construction. We still needed a glue to stick the circles together. 3M makes a special polystyrene adhesive but it is very expensive, and out of our price range. We wondered what other glues would work. We found a random bottle of Elmer's Craft Spray Bond that worked well, but we soon had used that up and couldn't find more at local stores. We bought a variety of adhesives that were advertised as "suitable for use on polystyrene". We soon decided the green goop that used to be polystyrene proved that not all of these adhesives were, in fact, suitable for use on polystyrene. We decided to try our household "go to", Liquid Nails. It worked better than anything else and became our polystyrene bonding adhesive of choice.

We had our polystyrene. We had our adhesive. The next step was to cut circles from our foam board. Although we were not able to master the CAD program we had available, we were able to use it to extract numbers for cutting out the circles that would form our plug. We drew a longitudinal cross-section of the sub interior. Then, taking cuts at intervals equivalent to the thickness of the polystyrene board from which we were cutting discs, we determined the diameter of the sub at that point. We cut some with a hot knife, but soon discovered this was neither time efficient nor a quality cut. We used a hack saw to cut rough circles out, then used a bandsaw for the precision cut. The discs to be cut could have had beveled edges; the taper angle was calculated on a spreadsheet using simple trigonometric formulas. The Craftsman tilthead bandsaw we were using had the capability of cutting angles, but we only discovered how to adjust it after the nose cone discs were cut.

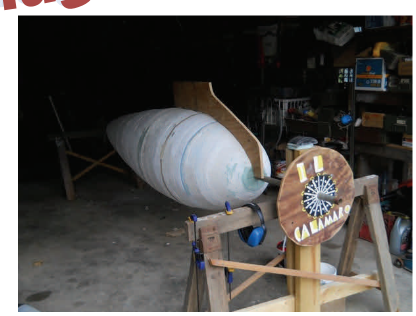
During all of this, we had slowly been finishing our spindle design. The basic design was two saw horses with a length of salvaged well-casing resting between them. We mounted a steering wheel to the pipe. The wheel had holes drilled in it every 22.5 degrees where we could insert a peg through the steering wheel and into a stop block; this acted as a brake.





Creating the Plug





Now we had the spindle, the foam circles and the adhesive. Now we needed safety equipment and tools: respirators, disposable gloves and jumpsuits, safety glasses, sanders, and a variety of other items. We went to Lowe's to see if they could sponsor these items. We had a detailed buy list and solicitation package. Once we got to Lowe's, team members Teddy and Sam approached management with the list. The manager on duty told us the local Lowe's donation budget was already allocated, but she really want to help sponsor the project; she agreed to let us purchase all items on the list at cost.

We still needed fiberglass and resin, however. We bought 27 yards of 60" 10 oz woven E-glass, 2 gallons of West System epoxy resin, 2 quarts slow hardener, 1 quart fast hardener, and 2 sets of resin pumps.

With the hole saw we purchased at Lowe's, we were able to drill holes in the foam discs so that they could be mounted on the spindle. A few things we learned were: polystyrene is very messy to drill through; it's hard to drill accurately and consistently through polystyrene; it was very important to have marked the circle centers before we cut the large circles out (a lesson we had thankfully learned previously during a sub profile mock up using cardboard); using a jig helped us cut more accurate holes. Some of the circles we beveled. All the circles in the tailcone were beveled.

There were plenty of scrap pieces of foam lying around and we used these to conduct a series of fiberglassing experiments. The experiments included: seeing how smooth fiberglass would lay up over a rough surface; the basic concept of waxed HandiWrap as our release agent on the polystyrene; laying up multiple layers of glass and observing their strength. Subsequently, we used these experimental pieces to practice adding a lip to a hole, glassing in hardware, and cutting through fiberglass.

Then it was time to assemble the plug. We glued sections of the plug together using the polystyrene discs and Liquid Nails. We glued about 5 or 6 discs together at a time. In total there were about 50 discs. We slid the pre-glued stacks onto the spindle, applying generous quantities of Liquid Nails in between each stack to secure the stacks together. Once all the stacks were on and glued together, we had a crude plug! The only problem was, although one stack of polystyrene didn't weigh much, all of them together along with the gobs of Liquid Nails weighed enough to cause our spindle to sag just enough that the discs wanted to pull apart. The first step of recovery was to clamp the discs together by pushing them inward and wrapping a lot of duct tape around the spindle where it protruded from the plug. One end of the spindle was fixed in a wooden block, but the other end was just resting on the other sawhorse; we hung a concrete block from the overhang at this end of the spindle. This made the sagging manageable and we were able to turn the assembly. We filled any gaps with Liquid Nails and imperfections with dry wall mud. We made a template from plywood to conform to the desired plug profile and shaved and sanded the plug until the template fit snugly. It took a lot longer to do this than we thought, but eventually it worked. Now it was time to lay down fiberglass!

Fiberglass Construction

We used tape to make 3 longitudinal stripes down the plug, 120 degrees apart. We worked one section at a time. The first layer all the way around was the hardest to lay down smoothly. The technique for the first layer was:

-Cover plug with HandiWrap. This keeps the resin from sticking to the polystyrene. Since we wanted to dig the polystyrene out later, this would make our job easier.

-Wax HandiWrap with Johnson paste wax. This is a safety measure to prevent resin from leaking through the overlapped cling wrap. Let dry.

-Cut a length of fiberglass. We used 60" wide fiberglass but wanted 30" sections, so we had an additional cut to make the cloth 30" wide. (60" wide cloth is cheaper by the yard than 30".)

-Lay the cloth down on the plug. Trim to size.

-Mix resin and hardener. Apply to fiberglass. We used squeegies. Let cure.

Our very first strip was layed down over wet wax. We could tell immediately that a) we had applied too much wax, and b) it was soaking into the fiberglass. After consulting with our experts, we decided the biggest drawback to wax-infused fiberglass was that it might compromise the strength of any glassed-in attachments we needed to make. We decided to start over, but used this strip to verify that we could turn our spindle and the glass would stick to the hull.

We built up one entire layer over the entire hull, then simply layed down subsequent layers, sanding in between layers, as necessary. A final coat of epoxy resin was added over all.

Areas to be cut out were mapped out on the hull. A combination of Rotozip and jigsaw was used to cut out the shapes.

Lessons for the Future

-When using a "growing boy" as pilot, plan for growth. Our primary pilot, already the tallest member of our team in September, grew about 3" from the time we finalized our hull dimensions to now.

-Learn how to use 3D CAD. It will save you a LOT of time!

-Make sure your measuring instruments are calibrated. We assembled our beam compass and discovered it was almost an inch off!

-People are generous with their knowledge. Ask lots of questions.

-When using a plug on a spindle, make sure your spindle is strong enough for the weight it has to support.

-The time you spend fairing your plug will have great pay off. If you want a beautifully smooth finished project, your plug needs to be beautifully smooth.

-Paste wax needs to dry before you lay down fiberglass over top of it.

Hatch

Research

We researched boating latches and hatches on the web. Size of hatch was a consideration since our pilot is quite tall and needed to be able to get in and out easily—especially in an emergency. We wanted the hatch large enough to be able to access the propulsion system and various interior items to do adjustments without having to reach too awkwardly. We also thought about the stability and ease of moving a large hatch and if it could be locked down easily and firmly over and over again. In case of emergency, divers need to pull the hatch off quickly and easily, but hopefully not damaging the hull itself.

A company in Michigan that makes quick release emergency latches for both boats and automobiles looked intriguing to us. It described that the latch could be quick released by pulling on a simple fabric handle. That was exactly what we were envisioning for out pilot, should he need to get out quick.

Design

We were also influenced by Old Saybrook High School's "Miss Jesse II". We liked the shape and location of their hatch. Our design was verified with cardboard mockup. Sam and Teddy cut out a hole from a very large piece of cardboard and elevated it on some chairs and had our pilot, Sam, climb in and out of the hole into "pilot position". They decided to make the size of hatch 2' x 3' keeping in mind all their needs and requirements.

The latch company could not be reached and after talking further on the subject, the team decided to stick with the simplicity rule. A simple spring latch was chosen that could be accessed easily from inside using a pin to the outside with a brightly colored neon handle in the pilot's peripheral vision.

Fabrication

A flange holds and supports the hatch in place and the spring latch locks it in a tight position. The hatch has a spring latch attached with a cup handle that lies flat to the outer surface. The cup handle is black and easy to spot against the bright yellow submarine exterior for emergency requirements and is located next to the spring latch.

Testing

Final testing will be conducted in the pool prior to race day.

Lessons for the Future

Starting sooner would probably be more helpful in testing the hatch and latch system for report purposes but we feel confident that our systems are well thought out.

Windows

Research

Adding windows to the submarine was necessary so that the pilot could see out and rescue divers could see in. Our first thought was to have an acrylic nose cone. We had talked to members of the Da Vinci II design team (entry in early ISR); they had made a fiberglass hull, cut off the nose, used it as a mold for a concrete plug and formed an acrylic nose over the plug. We did not have access to an oven that would accommodate the large piece of acrylic needed to made the nose we envisioned.

www.aecdaily.com
AECDAILY
Building knowledge and connections

AEC Daily Corporation
266 Elmwood Avenue, Suite 511
Buffalo, New York 14222 USA
877-566-1199 ext. 84
info@aecdaily.com
AIA/CES Registered Provider
AIA/CES Provider Number J624

Sponsored by:
EVONIK INDUSTRIES

Sam Carts

Has successfully completed the course

Acrylic Specialty Products: Inspirational Design Solutions

Course Number: AEC533 (EV-EN-53303-0314) on February 27, 2013
Certificate Number: 610167-09648
AIA/CES Learning Units: 1 HSW/LU - 1 hour program
This course qualifies for HSW
IDCEC Approved CEU: 0.1 HSW - 1 hour program. Course Code: CC-100852-1000 , Subject Code: 1-8 , Classification: Basic

Christopher Allen
Instructor: Christopher Allen

One of our hull team members became our acrylics resource, earning 0.5 CEU through an online acrylics course. Through the course sponsor, Evonik, we learned that there were a couple of acrylic fabricators in our area. We scheduled a meeting with one of them, Precision Plastics in Beltsville, MD, and brought our blueprints with us to the interview. In an eerie coincidence, design engineer Greg ____, turned out to be a backyard submarine hobbyist. He told us that the nose cone could indeed be made from acrylic, but that for their company to make it, it would be expensive and that the acrylic might thin unacceptably at the nose tip. He recommended we use multiple smaller windows like SpaceShipOne. We embraced this suggestion as something we could do at home.

Design & Fabrication

While the hull was being fabricated, we obtained a sheet of acrylic (36"x72"x.118") from the local home improvement store. They carried Optix acrylic. We conducted a number of experiments using small pieces of Optix until we determined that heating the acrylic to 230F (convection setting) for 5 minutes was optimal. We found that our procedure was more successful when the form was concave (acrylic sank into the mold) rather than convex (acrylic draped around a form). We also verified that a fiberglass form could withstand 230F. Furthermore, we determined that marine epoxy available at the local hardware store was a structurally sound adhesive for bonding Optix to fiberglass.

Once the hull fiberglass lay up was complete, we used the hull as a form. We protected the hull with HandiWrap, waxed the wrap with Johnson paste wax as a secondary release agent, and layed down three layers of fiberglass over the desired curve (using cheaper polyester resin and fiberglass mat) to make the mold for our acrylic windows. We designed a paper template for the window, taped it to the Optix pane and cut it out on a bandsaw using a fine tooth blade (ours was 12 tpi). We clipped the edges of the cut-out with wooden clothes pins, set the assembly on a cookie sheet and popped it in the oven for 5 minutes. When the timer rang, we had two people ready to work. One quickly removed the acrylic and dropped it in the form. The second applied as uniform a force as possible to the acrylic so that it would conform to the shape of the mold.

The windows were traced onto the hull. Using a combination of Rotozip and jigsaw, the shapes were cut out from the hull. Small lips were fiberglassed on the inside of the window cut-outs and the windows were epoxied to them.

Also, to plug the hole left by the spindle that the hull was mounted on, we opted to put a small domed window at the nose of the hull. The method described above was used for this window, as well, although the form for the dome was carved from polystyrene.

Lessons for the Future

- Acrylic forms best into a concave surface, rather than a convex .
- It is better to leave the acrylic in longer than shorter and some cases, longer than the suggested time.
- For a smoother cut edge, use a jig saw to cut out a rough edge and then a band saw to cut out a smoother and more precise edge of the shape you intend to cut.
- Best way to melt acrylic: Use three clothes pins and attach to the object you are melting, attach at every 120 degrees and then put on a cookie sheet. Wait until the acrylic melts until it touches the pan or becomes extra gooey. Now it is ready to mold!
- It is good to put a piece of felt onto the mold you are using before you put the acrylic onto it. Then put the acrylic on, and put another piece of felt on top. Effectively, you want to sandwich the acrylic before molding it.
- For smaller pieces of acrylic, it is best to press the acrylic into your mold by hand while wearing potholders.

Propulsion

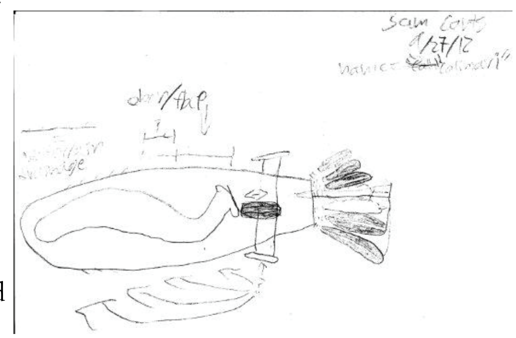
The combined Research and Design sections detail some of the chronology of the propulsion system from its initial conception thru the final design, with design specifics given in the Fabrication section and Lessons Learned is mostly distributed throughout the sections.

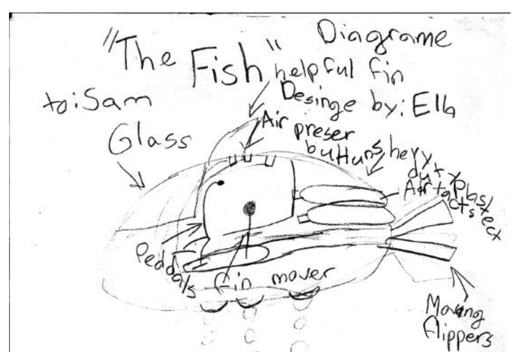
As mentioned in an earlier section of this report Carts Independent's interest was whetted by their recent introduction to SCUBA and SNAME Marine Forensics Conference in April 2012.

Research & Design

Our Conception: In exploring our depth of interest, possible approach to the project, and as a homeschooling exercise, a discussion was had amongst the initial team of three as to what form of propulsion was preferred, with especial respect to the classifications of entries into propeller versus non propeller, and one versus two man, submarines. The universal preference was for a non-propeller entry; the sense being that there was more room for imaginative designs there than with propeller-driven designs.

Sam the pilot offered his first notion of propulsion, a sketch of a design where multiple ping-pong-like paddles would hinge from the tail, swinging flat from outwards towards the submarine axis behind the sub, then return not flat but turned sideways for minimum drag. This enchanting concept suffered the hard scrutiny of skeptics, developing into the more easily realized concept of a linear thruster: Paddles hinging like the covers of a book on their spine would be thrust backwards spread open for maximum drag, then retracted forwards in closed-book form, spine first, for minimum drag. This concession to perceived manufacturability proved no impediment to the enthusiasm for the concept; this 'book' model has remained central to the project from that point.





There ensued long discussions over the next several months over many considerations and ways to overcome or make best use of them. Some reached seemingly obvious conclusions (bearing validation upon water testing) and some remain unresolved, requiring a choice of the least unlikely option or the infinitely frustrating random choide between options. Here are several considerations:

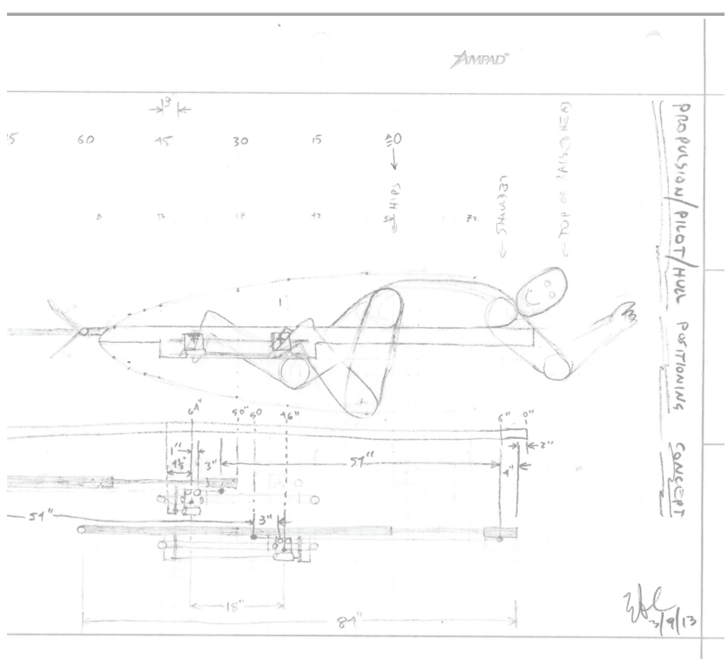
Pilot Position: Multiple issues raised themselves demanding solution. Minimizing what would later be learned to be “form drag” required the pilot to be head-forward or head-backward prone or supine. Recumbent bike positions were eventually abandoned for that reason. Head-forward both allowed the major muscle groups (legs) to be at the rear as well as the eyes to be in the front. Prone vs supine allowed a slightly more natural SCUBA position but importantly allowed natural vision of the course markers on the bottom. Eventually head forward prone was selected for the pilot position.

Power Delivery: Step vs Circular vs Other. A trim hull shape implied likely space constraints on foot position. Circular pedal motion would require hull diameter at the feet to be not only the foot length but in addition the diameter of the rotary path of the feet. A linear, purely forward/backward, pedal motion would allow a smaller diameter hull at that point.

The point was raised that in certain exercise forms which require best power output, such as rowing and sculling instead of merely the legs the entire trunk including back and arms are used. Our failure to envision a method of harnessing full-trunk power within a low-profile hull caused us to abandon this likely superior power generation method, for now.

Keeping the trunk straight but involving the arms in the power stroke was also raised as a possibility, but the onset of design befuddlement caused this to likewise be set aside, for now. Besides, the pilot would likely be needing arms for depth control, deadman's switch operation, air system monitoring, signaling and perhaps other tasks.

Efficiency and Power: Kinesthesiologists were consulted regarding various aspects of the propulsion. It was learned that approximately ¾ horsepower, or 550 Watt is the best case momentary human output, with ½ horsepower sustained for few minutes (100 m course run at 1 mph would last 3 minutes 45 seconds, 4 minutes with acceleration zone time) being more realistic. In water, constrained and breathing SCUBA the available power was thought to be more on the order of 1/3 horsepower, or about 250 Watt.



In addition the optimum leg angle for power output was sought. Although maximum force is possible at near-full (straight) leg extension the speed of foot movement is minimal. At high step (upper leg straight outwards) the highest foot speed is possible but the leverage lessens the maximum force possible. Likely the speed times force (power) would peak somewhere in between. It was learned and accepted as postulate (i.e. without literature reference) that peak power would occur when the upper and lower legs were 60 degrees from straight.

For a normal stature human form that 60 degree bend occurs at a slight stroke length (difference in height between the balls of the feet) of only 5 or 7 inches. At high step the stroke is close to 18 inches. For reference, a bicycle pedal circle is about 13 inches in diameter.

At high step the minimum interior hull diameter would be dictated. A 6' pilot from back of hips to patellar tendon/tibia with the femur and tibia at right angles has a 'diameter' of just over 24”. (Unfortunately in case of youthful pilots within the span of six months this can expand to 27”!!). A 27” OD hull provides 1” for hull thickness, 1” for back padding and 1” for knee clearance on a normal pilot or the decision to forgo full high-step strokes on an overgrown ones.

Alternate vs joint leg thrust, and single vs dual thruster: Related to the whole-trunk extension consideration is the question of whether the legs ought to operate together as in jumping or alternately as in walking; which allows higher delivered power? Although the complexity of the interior system was increased slightly by allowing the feet to operate independently that method was chosen as it allowed either alternate or simultaneous operation according to best performance of the pilot. In addition it was supposed that some amount of left-right steering would likely be possible with independent operation.

Theoretical Efficiency: On propulsion efficiency opinions were solicited and observations were offered by a neighboring wild-haired physicist:

> -Propulsion can be seen as a transfer of momentum to the water;
>
> -Momentum is proportional to both the velocity and the mass of the water, so that to double the momentum either the mass or the velocity of the water should be doubled;
>
> -Energy put into moving water increases as the square of the velocity and proportionally to the mass of that water (E = m * v^2) so that doubling the velocity of the water requires four times the energy.
>
> -Thus it is better to double the momentum by doubling the mass at the same velocity (which requires double the energy) than it is to do so by quadruping the energy in order to double the velocity. Rephrased, moving more water slower is more efficient than less water faster.

The implication of this is that there are prospects for a better propulsion system with linear thrust versus a propeller. Other than manufacturing issues with this novel system the team is intrigued to see whether this all may be true, or if not, why not.

Limitations: Caution in enthusiasm was reinforced when a fundamental limitation of low-speed high mass propulsion system was discovered: While the thrust and starting 'torque' may be huge when moving very large masses of water at low speed the theoretical maximum speed of that system would be less than 1 mph! At that vehicle speed the thrust water would have a stationary framework speed of zero, and thus the vehicle would receive zero thrust forward.

In reality the maximum speed would be less than the maximum thruster speed because as the thrust decreases but before it reaches zero it will equal the drag force and at that point there will be no net acceleration. On the other hand, as the sub approaches that maximum speed the force offered to the pilot will decrease and thruster speed will be higher than at low sub speed.

Gearing: This limitation (high thrust at low speed and low thrust at high speed) begs variable, or switchable, gearing but such a design was out of the scope of this team, for now. Instead a high 'gear' ratio of 3:1was chosen as reliably manufacturable and not too high to perhaps impede starting torque. That is, the pilot moves his pedals 1/3 as far as the propulsor, the propulsors move 3 x faster than the pedals, and the pilot pushes pushes 3 x as hard as the propulsors.

Unpleasant Historical Discovery: After inventing this propulsion method and developing it substantially, during internet searches for prior ISR records, the 1991 Battelle entry which used the same basic propulsor concept was discovered! See MTS '91 Conference Procedings, Vol 1, "The Spirit Of Columbus: An Innovative Approach to Submarine Propulsion". You can see The Spirit of Columbus in action in the Vimeo video referenced in the bibliography.

Differences between that and this implementation of the propulsion type include it being 2-man vs single pilot, ocean-going vs test basin, and single propulsor vs double propulsor. The stroke of the 'Columbus' propulsor was 48". Calamaro's propulsor stroke is variable (actually, Columbus' stroke also was probably variable) but has a maximum stroke of 54". It appears that Columbus' propulsor area was ~1 diameter wide by ~0.6 diameter high, so ~3.6 ft^2. Calamaro's two propulsors currently are each 1' x 2' for a total of 4 ft^2 however water testing has not allowed optimization of the size. Solace is taken in that it is within a factor of Columbus'. Columbus was about 1' longer with the same diameter. Disregarding speculation on drag, the entrained volume was larger for Columbus so acceleration ought to be better with Calamaro. In 1991 it appears the Columbus fell prey to the ocean currents which buffeted it and drove it into course markers. We hope to fair better in the quiet waters of David Taylor.

Fabrication

The propulsion system consists of the Frame, the Frame Mounts, the Pilot, the Pilot Mount and the Propulsors. Nominally no thrust is transferred to the Frame at all but rather directly to the pilot's feet, so the Pilot Mount, a backpacking hip belt, is a critical component of the system.

The Frame: The frame consists of one unifying element (an aluminum T bar) holding two symmetrical systems, one for each leg. Two channels contain a pushrod each sliding within. The frame also consists of pedals mounted to blocks, guide rods on which slide the pedal blocks, cables which transmit force to the pushrods and pulleys which generate mechanical advantage.

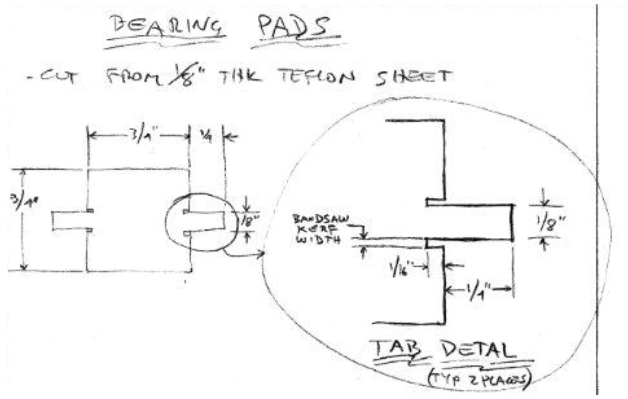
The major metal elements are all aluminum except for the guiderods which are steel. Hardware is generally regular zinc plated as the total wet time for this submarine is expected to be less than two months. The wire rope is 1/8"is stainless. The weave was chosen as being particularly flexible to minimize power loss.

Each side's pushrod is about 8' long and are constructed of sections of 3/4" x 3/4" aluminum tubing 1/8" wall joined by 1/2" square aluminum bar. The propulsor attaches to the aft end of the rod with another 1/2" square bar which is pinned to the rod.

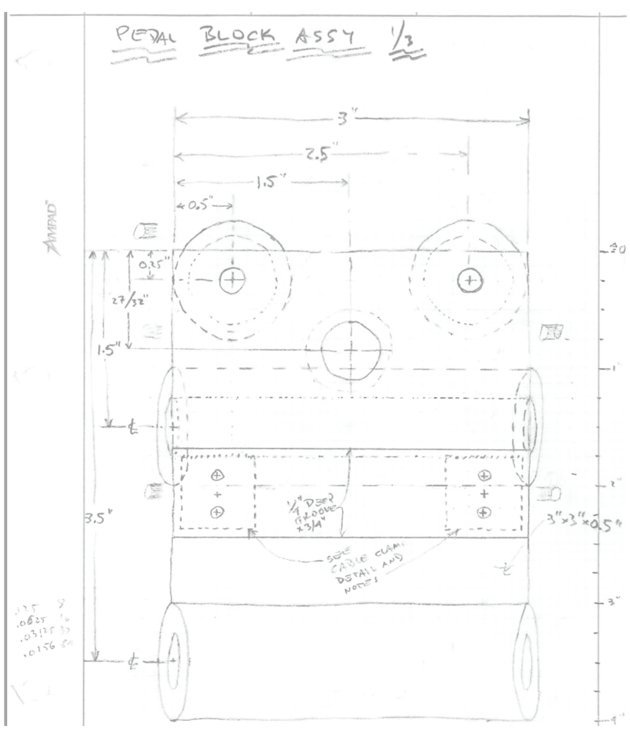
Steel rope (cable) transfers power to the rods. One attachment is at the forward end of the rod; it pulls the rod afterwards during the power stroke. The aft end attachment retracts the pushrod and is a keyhole shaped hole into which the cable with a crimped 'stop' is fitted. The entire cable system for each side is one cable so a single tensioner serves the whole side. At the front cable attachment the cable passes into the pushrod and crimps to a threaded stock. The threaded stock passes thru a clearance hole in the end cap of the tube and is pulled forward with a wingnut, tensioning the entire system.

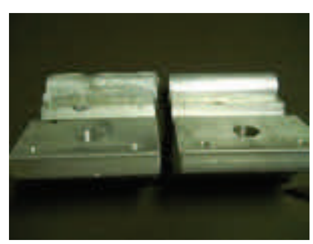
From the front of the pushrod the thrust stroke cable travels aftward around a pulley on the pedal block then forwards around a pulley fixed to the frame then aftward again to fix to the pedalblock. The retract stroke cable is for/aft symmetrical. Because the thrust stroke and the retract stroke cables end at the same spot the two cables are one but they can be considered separately.

Zero-clearance teflon bearing pads provide low friction constraint of the pushrods. The pads are 3/4” x 3/4” with 1/8” wide tabs extending outwards 1/4” past two opposite ends. The tabs are inserted into two 5/32” holes 3/4” apart. This attachment method works well because once the pushrod is inserted into the channel there isn't enough room for the tabs to pop out. Five sets of pads (four pads each set: Top, bottom left and right) support each rod. Three sets are mounted to each rod and two sets are mounted to the rear of the channel.



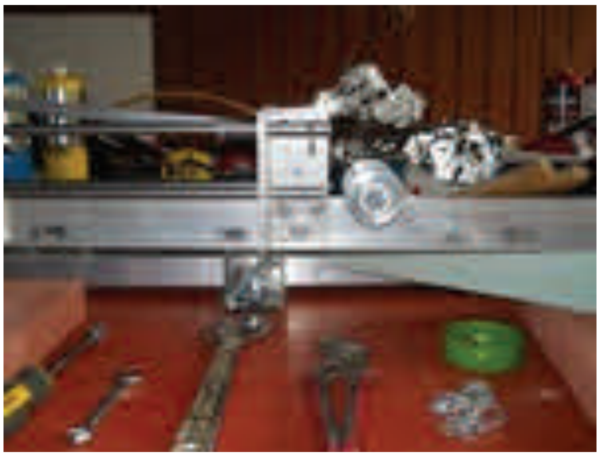
The pedalblock has two tubes sliding on guide rods for/aftwards a maximum of 18”. Manufacturing design failed to take in to account the high degree of parallelicity required of the pedalblock guide rod tubes. As a result the zero-clearance teflon bushings are only left on one of the two guide rods; the other guide rod has ~1/16” clearance, which should not be troublesome but it rattles a bit.



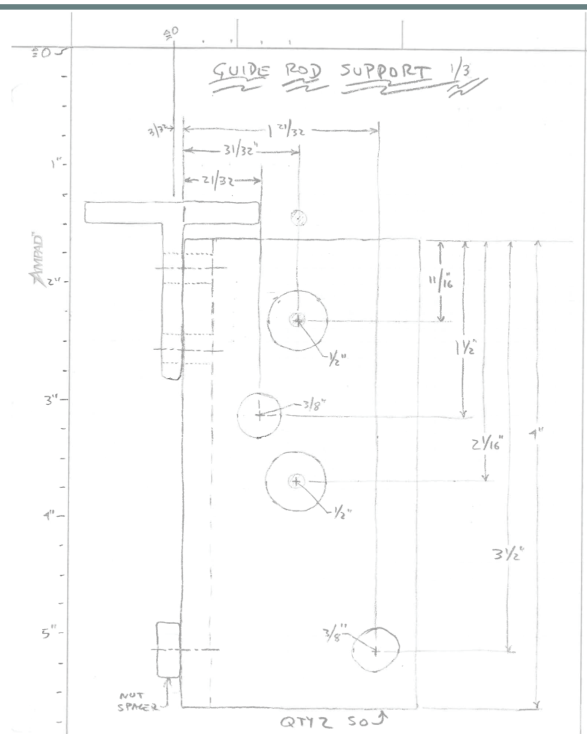


PEDAL BLOCK

The pedals are bicycle pedals, the “clipless” SPD type which allow pulling of the pedals 'up'wards, required for retracting the propulsors. Both prospective pilots are cyclers who use these types of pedals and are comfortable with the rapid disengagement maneuver which allows somewhat more graceful crashes than do toe straps. This is a strong positive safety characteristic.



Guide Rod



Frame Mount: The frame is centered on the submarine’s axis and the pilot rides the frame somewhat like a witch on a broomstick. At the tail the frame is suspended from a bracket that hangs from the inside of the hull. The last ~1’ of the tail is removable to allow removal of the propulsion system. The forward end of the frame ends at about the pilot’s neck. It is supported from below by an inverted V which straddles the airtank.

Pilot and Pilot Mount: The pilot pushes aftward on the pedals to transfer momentum to the propulsors and gains the equal and opposite momentum forwards. By strapping him with a backpacking hip belt to the submarine that momentum is shared with the hull. The hipbelt mounting bracket is adjustable in order to allow both for differently sized pilots and to allow for design uncertainty. The hipbelt has a SCUBA weightbelt style buckle to allow for quick egress. The location

of the hipbelt and the pilot's weight belt overlap so when the pilot enters the sub and clips in to the pedals he then drops his weight belt within the sub and buckles in to the hipbelt. Upon egress the pilot is significantly positively buoyant without his weights.

Propulsors: The two pushrods exit the frame with ¾" clearance between them. In order to be allowed to operate independently the propulsors must each stay on their own side of the vertical plane of symmetry of the hull. I.e. the left propulsor must be centered to the left of the axis of the submarine. This off-axis thrust will apply a torque to the pushrod and thus to the submarine as well. These torque effects must be understood and be or be made acceptable.

The pushrod is essentially pulled outward during the thrust stroke. The single foot force of the pilot will be in the area of 1.5 x his body weight, or 300 lb. The 3:1 gearing will reduce that force to ~100 lb. If the center of force is 6" from the pushrod axis (it will be) there will be a torque of 50 ftlb on the sidewall of the channel. Wild haired physicists would feel fairly comfortable hanging their healthy bodyweight on the side wall by their fingers. Thus the (still untested) frame channel sidewalls are deemed adequate. Time will tell whether repetitive stressing will have an effect.

The same 50 foot-pound torque will be applied to the hull. The submarine will 'fishtail', wag from side to side, as it moves through the water. The stroke period during maximum thrust might be 3 seconds (one left and one right). The mass of the sub will be ~1500 lb with entrained water so it is hoped that the wag will be insignificant or minor.

The first portion of the thrust stroke is spent without thrust while the flaps open fully. Wider (distance from spine to outside edge) flaps will take a longer portion of the stroke to open. This and the torque both impel the design towards a narrower flap. No intrinsic penalty is incurred for taller flap. Thus a 2' tall by 6" (each flap) design was chosen to start with.

The propulsor consists of the flaps which open and close, the hinge or spine which holds them, the flapstops which don't allow the flaps to open greater than flat (and which incidentally transmit all of the torque), the offset and the pushrod mount.

The propulsor mount is a ½" square which inserts into the ¾" square pushrod. Steel strap ¾" x 1/8" forms both the lateral offset and the flapstops. The flaps are 0.080" Lexan. The hinge consists of nylon fabric glued to the edge of the flap. The two fabric pieces are pinched in between two ¾" x 1/8" Aluminum pieces.

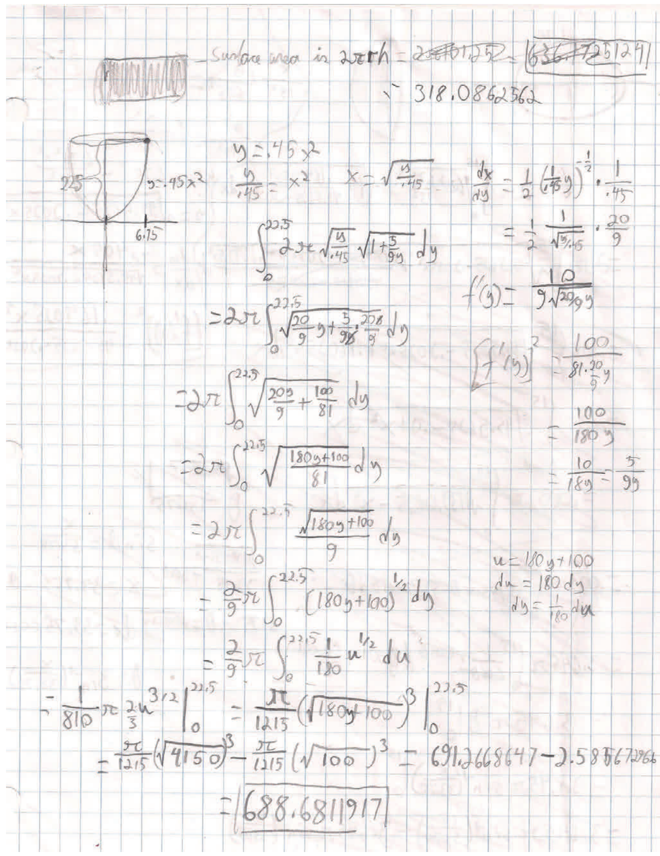
The flaps might both fall open to the same side if there is nothing to prevent them from doing so. The Aluminum spine is formed around a ¼" rod which prevents this.

Lessons for the Future

The design is rife with mostly reasonable engineering assumptions which haven't been proven. The primary lesson for the future is to allow for much slower progress than might be expected and to work quickly— schedule leeway is valuable and lack of it results in risk.

Buoyancy & Trim

Research



In order to calculate the buoyancy of the submarine a number of steps were taken. First, the volume of the hull, propulsion system, and air tanks were found – all the parts of the sub that were not water. The pilot was assumed to be neutrally buoyant and the dive planes and steering mechanisms were not considered. The hull volume was found by using the surface area calculations determined previously and the approximate thickness of five layers of fiberglass. As the air tanks we were using were a specific type, we were able to find their dimensions online. The volume of the propulsion system was impossible to find directly, so it was calculated by using the density of 2024 aluminum – the primary composite of the system – and the weight of the propulsion system. These calculations enabled us to find the buoyancy of the non-water parts of the sub, and thus find the amount of scored, close cell foam that we needed to add along the hull interior for buoyancy.

Design & Fabrication

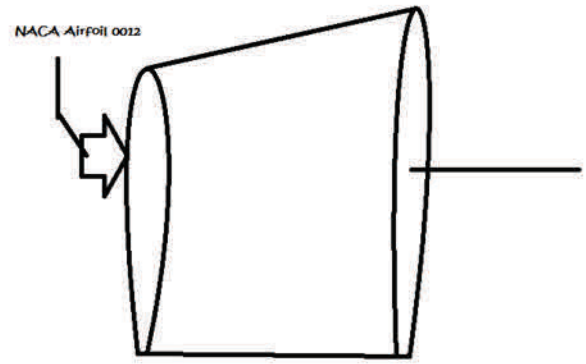
Velcro strips along the bottom interior of the hull will secure weights. The trim weights will be made from small bags made from recycled feed bags filled with steel shot. Foam will be attached to the interior of the sub as needed according to buoyancy calculations and as verified by pool testing.

Lessons for the Future

Keep calculations in order, together, and clearly marked so that they may be used months after they are originally determined.

Steering

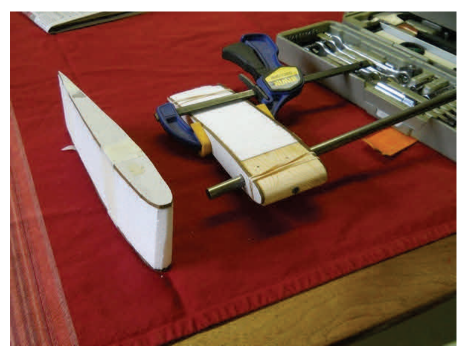
Research



The first thing that we did was look at other submarines to see examples of what they did for their dive planes we found that most dive planes were very thin and typically very small in comparison to the submarines. We went through many different shapes and different ways that the dive planes would penetrate the hull and different pulley systems and how the dive planes would be controlled. After asking around we decided to have the dive planes controlled by elbow movement instead of wrist movement because it would be easier for the pilot to make an elbow movement than a wrist movement in the submarine.

Design & Fabrication

After some research on airfoils we decided on NACA airfoil 0012 then after the hull was fiber glassed we looked at the hull and decided that a reasonable length for the dive planes would be 12 inches. We decided that the sweep would be 1 inch and we printed out some templates to use and cut them out of Masonite then tried to just glue the Masonite to a slab of 12 inch long condensed polystyrene but when sanding down the polystyrene (with the appropriate safety equipment) the Masonite fell off the polystyrene so we decided to screw down the Masonite to the polystyrene so that when we were sanding down the polystyrene the templates did not fall off. Right now we are trying to decide if we are going to shape the planes to fit more comfortably against the hull or to leave them as is.



Lessons for the Future

- More research needs to be done
- Always screw the templates on
- Include more chocolate
- Do more research on airfoils
- Think more in-depth on how steering is controlled
- Explore all resources before pursuing to sand polystyrene

Life Support

Research

VO2 Max testing of primary pilots at the University of Maryland to determine air consumption needs under stress. The report suggests a 40 cubic foot tank would be sufficient per run and would be in compliance with ISR remaining air requirement.

UNIVERSITY OF MARYLAND

Department of Kinesiology
2351 School of Public Health Bldg
College Park, Maryland 20742-2611
301-405-2450 TEL
301-405-5578 FAX
www.sph.umd.edu/knes

Date: March 2, 2013

From: James Hagberg, PhD
Professor of Kinesiology and Medicine

To: Il Calamaro Human-Powered Submarine Team

Re: Human-Powered Submarine Trial Compressed Air Requirements

I have based the following calculations on the information you provided in a recent email concerning the different segments of the human-powered submarine trials that must be supplied by on-board compressed air tanks.

The first segment was 3 minutes with the pilot in the sub with no exertion. Normal resting ventilation is around 10 liters/minute. This would result in a requirement of a total of 30 liters for this segment. However, to be conservative and to account for the fact that it is highly unlikely that the pilots will be truly completely at rest in this situation, I am going to base the requirements for this segment at 30 liters/minute, for a total compressed air requirement of 90 liters.

The second segment includes both the minute for the pilot to ramp up to speed and the minute of the pilot exerting at cruising speed. For these calculations I based the air requirements on the maximal ventilation that the two pilots reached during their recent VO_2max tests in our laboratory. Somewhat fortuitously, Sam and Karl had very similar maximal exercise ventilation rates during these tests. Their values were 140 and 143 liters/minute, but I will use a conservative estimate of 150 liters/minute and these calculations then apply to both of them. For these two minutes I, again very conservatively, assumed that they would be at maximal ventilation the entire time, which will clearly not be the case. With all of these conservative assumptions built in, the total air requirement for this two minute segment of the trial is estimated to be 300 liters.

The third segment of the trial while on the on-board air supply tanks is the two minutes of recovery. Once the exertion is stopped, expired ventilation rates would decrease back to baseline levels of ventilation at an inverse logarithmic rate with a half-time of approximately 30 seconds. However, again to be very conservative, I assumed that the ventilation rates during this entire segment would also be the level required during maximal exercise in our laboratory. Thus, again using the ventilation rate of 150 liters/minute, the absolute total air requirement for this 2 minute segment would be another 300 liters of air.

1

The total requirement is then the sum of these three components: 90 + 300 + 300 = approximately 700 liters of compressed air. In reality I would probably actually expect this value to be around 500 liters without all of the very conservative assumptions I added to the calculations.

Knowing that in scuba tanks 1 cubic foot of compressed air equals 28.3 liters of air at normal pressure, a 40 cubic foot tank would hold 1132 liters, a 60 cubic foot tank would hold 1700 liters, and an 80 cubic foot tank would hold 2265 liters.

Thus, from these calculations I am pretty confident that a 40 cubic foot tank would have more than enough air to supply these three segments. You had mentioned that the tank had to still have 25-33% of the air remaining in it at the end of the trial (I think that was roughly the range???). Using a 40 cubic foot tank with the 700 liter air requirement for the trial would still leave >35% of the tank filled at the end of the trial.

Another consideration that may come into play is the fact, at least in their current states, Karl would be generating about 6% more horsepower or joules at this same level of ventilation as Sam.

2

Design

A mockup of submarine using 2x4s and cardboard was made to verify fit and placement of the air tanks. The design calls for a 40 cubic foot tank affixed to the submarine frame with hook and loop fasteners. There will also be a 6 cubic foot pony bottle attached near the escape hatch with hook and loop fasteners.

Fabrication

The 40 cubic foot tank with primary regulator will be secured to the frame of the submarine using hook and loop fasteners below the drivers' chest. This will allow for the driver to have access to the valve and regulator during the race. The placement eliminates the possibility of the regulator line becoming pinched or getting tangled in the drive system. The 6 cubic foot pony bottle with regulator will be attached near the escape hatch and will allow the driver to ascend to the surface without a rescue diver if necessary.

Lessons for the Future

When designing the submarine it would have been helpful to have the air tank available in order to choose placement in the submarine. Using rental equipment does not allow for have the life support system full assembled while building the submarine. When planning for future ISR events we will purchase all life support system components before beginning the design and construction process.

Emergency Systems

Research

A series of tests was done in the early phase of this project to verify suitable buoy materials that were readily available. These included bamboo, close cell foam, other foam. The bamboo worked well, but we found that the chamber that had been empty at the beginning of the pool tests, now contained some water.

When we began designing the emergency strobe light system, we had the idea that lights in the end of the stabilizer fins would be cool and useful. Could we design a light that would get USCG approved, as required by the ISR contest rules? We researched the USCG approval process. After seeing what was required on the USCG website, we called the local station in St. Inigoes, Maryland, to confirm our understanding. The process is indeed designed for products which will be mass-marketed or for ocean-going maritime vessels with one-off special applications. The approval process is not designed for backyard hobbyists. Thus, we decided to include a USCG approved light in order to meet ISR requirements, and to add stabilizer fin lights, if time and resources permitted.

Design

The rescue egress will be outlined in fluorescent tape and has an inside/outside release mechanism . This is described more in the hatch section of this report. The crew is retrained in the prone position using a hip harness with a quick-release weight belt buckle and SPD bicycle pedals in the drive train (similar to a bicycle). All emergency latches, clips, etc., will be painted fluorescent orange, as will propeller flap tips. The crew will be visible with acrylic windows placed in the submarine nose so that the pilot can see out and so that he is visible to rescue divers.

A Navi Light 360 was selected as our USCG approved strobe light . It's high visibility, low profile, large on/off button and reasonable cost were all key features in choosing this light. It will be held on by a magnetic plate. We contacted the manufacturer to verify that the light, originally designed for surface use, would work at a depth of 30 feet, when submerged for a week. We also asked if the pull of the magnet would be stronger than the buoyancy force on the light, and they predicted it would work. We will verify this concept during testing at maximum submarine operational depth.

Mike Campola, an electrical engineer at NASA, is helping us work on additional lights. He came to one of our regular sub meetings to show us his preliminary design and to make sure that the emergency systems engineer understood how the circuitry worked.

The emergency buoy will be made from three inch PVC pipe capped at each end and painted a fluorescent color. The high visibility, 1/16" high strength line was purchased from an eBay store specializing in wilderness survival. The reel, an old fishing reel belonging to the father of our emergency systems engineer, will be mounted in the submarine. The deadman switch will be a pin attached to a wrist band that the pilot will put on when he enters the submarine. This design is similar to a jetski wristband emergency lanyard.

Testing

We conducted a variety of tests on the buoy system. First we tested the reel to make sure the line would flow freely when the buoy was released. Then we checked to make sure the buoy would deploy quickly. We also wanted to add a flag to project upward from the buoy when deployed, so we tested ballasting the buoy. Final testing of the system will occur later in our full assembly pool tests.

Lessons for the Future

-PVC filled with foam does not necessarily float faster than without foam.

-Trying to force a buoy down is very difficult.

-Mr. Campola is a very experienced electrical engineer. It turns out he also knows how to work with composites.

Competition Day Preparations

Pilots

Pilots were not chosen specifically because of their fitness level but the initial pilot was a fit 6' sixteen year old. An almost exact same-sized additional pilot, a fit Marine, was added to the stable. Six months later the secondary pilot is the same size but the primary pilot has managed to grow several inches, limiting knee range of motion.

Physical Training & Conditioning

Both in good shape, so increased fitness levels.

SCUBA Training & Certification

All in-water participants come to the project with preexisting SCUBA certification.

Transport Vehicles

Local movement of the submarine is accomplished with a small three-wheeled cart evolved from a heavy duty hand truck. The hand truck wheelbase was about 15" and the submarine diameter is 27" so the wheelbase was widened to 28" in order to fit thru commonly 30" wide doors while providing much better lateral stability. An extension was added to the handle end of the hand truck, extending the length by 4 feet and adding a steered wheel and towing handle. Two mounting locations for hull-shaped supports are provided and are trusted for local operations but during highway transport additional foam block supports will be added to other locations along the hull. The steered wheel is solid. The inflated main wheels will be mostly filled with water for raceweek in order that the cart have at least slight negative buoyancy. Tiedown straps will be used even for local transportation.

A 5' x 8' expanded metal bed open trailer with ramp was obtained for the duration of the race. It will suffice without modification.

Final Submarine Testing

The hull is currently whole but without any appendages or hatch, windows or tail cuts. Once the hatch and tail are cut the propulsion system will be rough-fit and floated in a shallow pool. It is only then that a realistic fit of pilot in wetsuit can be made. Following that the window, marker light and emergency buoy cuts and the dive plane pivot holes can be positively located and drilled and the pilot hipbelt mount location and the propulsion frame mount locations can be laid up. Likewise the stabilizers will be added.

Safety protocol for the pilot during fitting and testing are probably as important as during the race, but we will be on our own instead of under the auspices of the race week staff. Initial fitting will be done: In the shallow end of a pool; with the hull tethered to the side wall; without hatch; with full tank of air and a secondary regulator sitting outside the hull; with multiple on-hand attendants.

Hatch-on escape testing will be conducted repeatedly starting with the shallow end of the pool and progressing to the deep end. Testing will be repeated with the emergency buoy.

Initial hull with propulsion testing will be done statically, propelling against the wall of the shallow end of the pool at zero water speed. Loose sub testing will be done with the hull leashed to above the waterline, with full complement of primary and backup air tanks, with two SCUBA divers standing by.

Lessons for the Future

This project has been greatly aided by ready access to local pools which are especially valuable during the winter months. Establishing good relationships with multiple levels of pool management (for example immediate pool management and their County supervisor) early, keeping management apprised of upcoming pool use and project updates help establish and maintain access to pools. Pools which serve the rescue diver community are used to SCUBA operations and might not have negative visceral or insurance reactions to pool use requests.

Budget & Funding

Category	Amount Spent
Development (original design research material)	$375
Hull	$1185
Windows	$30
Hatch	$20
Propulsion	$1300
Buoyancy & Trim	$220
Steering	$30
Life Support	$750
Emergency Systems	$65
Race Day Logistics	TBD
Documentation	$30

Donors

Knights of Columbus, John F Kennedy Council, Accokeek, MD

St. Mary's Sodality, Clinton, MD

Lowe's, Waldorf, MD

Jimmy Walls & Mid-Atlantic Foam, Fredericksburg, VA

Ferris Apiaries, Marbury, MD

Josh Urban: Join the Revolution to Overthrow Bad Music!

Bike Doctor, Waldorf, MD

Tony & Gayle Carts

Marianne Retrum

Anne-Marie Ramsey

St. Mary’s Church Sodality

Conclusion

The building of the Il Calamaro submarine was a sometimes fraught and difficult, but ultimately rewarding, experience. In the beginning it was the idea of one family, but the project quickly grew to four. Together, we helped plan and design our magnificent creation; through much joking and chocolate we were able to focus on achieving our goals. This whole project has been a very rewarding task for everybody on the team; we learned how to use fiberglass as a means of construction, how to plan, organize, research, and basically manage the construction of a submarine. Through thick and thin, our whole team persisted to build a masterpiece of modern day marine technology that we hope to race in the 2013 June International Submarine Races.

Acknowledgements

Special thanks to:

The Companies that helped:

Raytheon

Precision Plastics

North Point pool staff and Charles County Parks and Recreation

The Studio Cooperative

Bryan's Road Building Supply and staff

Sweet Composites

NaviSafe

NAZ Autobody

The People who helped:

Greg Ferris

Tim Caffarella

John Harmon

Hans Haucke

Carl Gotzmer

Chris (mechanic at Bike Doctor Waldorf)

John Balazek

John Hollyfield

Ray Rye

Professor James Hagberg, Staff and UMCP Grad Students

Deborah Stanley

Ann Marie Ramsey

The Carts-Ingram Family

Fredrick Jeffrey Frese

Mike Campola

Russ Elkins

Joe Blue

Chris Satterwaite

Team Member Reflections

Sam Carts (Age 16) & Teddy Schwalm (Age 13)

Why do you get involved?

Sam: to get a more hands on approach to science. As I am homeschooled, this was hard because I had no science teacher or lab. The International Submarine Race was the perfect solution to this problem. I jumped at the opportunity.

Teddy: I got involved because I thought it would be fun and a great way to learn. It has been a good semi-hands on experience for me. I have learned a lot, but I wish I could do more hands on work.

What did you expect from the experience?

Sam: to build a submarine and race it. I didn't expect this huge black-hole for time to appear. Its been a good experience though.

Teddy: I didn't know what to expect but from what I heard, it sounded like a cool project.

Did it meet your expectations?

Sam: yes, because the project is well on the way to being done like I imagined. No, because it did not go as magical and easy as I had planned. Overall, I should have expected it to be a harder project.

Teddy: yes, it was fun, as expected. Its been fun.

What was the most enlightening thing you learned?

Sam: How to fiberglass.

Teddy: How to fiberglass.

Did any aspect inspire you to keep pursuing a topic?

Sam: because I am the pilot I need to be extra fit. This aspect inspired me to purse getting in shape. Its been working so far! I just hope I can stay inspired till the race!

Teddy: no, but I enjoyed it all and would like to do it again.

What would you do differently next time?

Sam: lots of things. See lessons learned.

Teddy: a bunch of more research and a propeller competition.

Abigail Gerstman (Age 12)

I joined Il Calamaro because I want to become a marine biologist and I decided to take a delve into the engineering aspect of marine biology; marine technology. This is a good experience for me to learn science from a Catholic perspective (pretty much nonexistent in a public school). As a Catholic, it is very important for me to have that experience in my life.

I honestly did not know what to expect from this experience. I knew that there would be a lot of engineering and hard work involved. I think that we accomplished more than I expected, especially since we are the youngest team to ever enter the races

One topic I want to pursue is that when I was researching marine mammal pectoral fins, I found that humpback whales have little tubes or bumps in their pectoral fins. As an aspiring marine biologist, I am interested to find out why they have those bumps.

Next time I think we defiantly need to do more research. I also think that our meetings should have a status report ready to present to the rest of the team about the progress that they made on their topic. These status reports would make sure that everybody is up to date and also have us practice on presenting to groups of people, which is always a good skill to know.

Lydia Kivrak (Age 15)

I got involved in the submarine project because I thought it sounded interesting and because I wanted to exercise the knowledge that I was currently learning in my physics class at CSM and that I had learned last semester in my calculus class. I expected to use this knowledge to help with some of the vital calculations surrounding the construction of the sub. My expectations were met when I had to calculate the surface area and buoyancy of the submarine

The most enlightening thing I learned was that it's important to keep calculations and other paperwork in order, so they can be easily found and used again. I was a little inspired to keep learning physics, even after my class was over. One thing I would have done differently next time would be to keep the meetings more on track.

Elizabeth Gerstman (Age 9)

I didn't expect most of it to happen. I didn't know people would trust me with a screwdriver! The most enlightening thing was when Mr. Marty and Sam gave me a jigsaw and told me to cut windows from acrylic plastic! Next time I think we should stay a little more focused on the meetings.

Sophia Gerstman (Age 7)

I wanted to help with the submarine because it sounded like a lot of fun. I enjoyed helping with the testing of the submarine part in the pool. I liked working with the buoy to try and get the flag to rise first. Being in the pool made me want to learn more about testing underwater and scuba diving.

APPENDIX

Bibliography

INTERNATIONAL SUBMARINE RACE & HUMAN-POWERED SUBMARINES

Merry, Stephanie L. "Advances in the Design of Energy-Efficient Submersibles, Part I: The Design Process." Institute of Sound and Vibration Research. <http://www.focus-offshore.com/Docs/S&BINTRE.pdf>

Merry, Stephanie L. "Advances in the Design of Energy-Efficient Submersibles, Part 2: Outstanding Design Solutions." Institute of Sound and Vibration Research. <http://www.focus-offshore.com/Docs/S&BINTRE.pdf >The Engineering Design Process

McAuliffe, K. "Subcycles." Omni. February 1992, Vol. 14 Issue 5: 50+.

"International Submarine Race." Machine Design. 23 August 2007.

"'Spirit of Columbus' Garners Composite Award at Sub Races." Design News. 16 December 1991: 34.

DeRoos, B.G., A.A. Alten, K.B. Scott, D.E. Guza, G.R. Wilson and F.B. Stulen. "The Spirit of Columbus: An Innovative Approach to Submarine Propulsion." An Ocean Cooperative, Industry, Government, Academia, 10-14 November 1991, New Orleans, Louisiana. Washington, DC, Maritime Technology Society, 1991: 516-524.

Child, Malcolm S., Alberto Cangahuala. "Sea Beaver: Design, Construction, and Performance of a Human-Powered Submarine." Marine Technology. July 1994, Vol 31, No 3: 231-237.

Benetti-Longhini, Leo, Bryon A. Pardue, Scott Turner. "Design and Fabrication of the Torpedo II Human Powered Submarine." Human Power. Fall 1993, Vol 10, No 4: 3-7.

DeRoos, B.G., Foster Stulen, Rom Ramsey, Dave Carey, and Michael Neal. "A Human-Powered Submarine Design Process." Human Power. Fall 1993, Vol 10, No 4: 9-14.

Scholl, Ray and Ed Leibolt. "The VICTORY Human Powered Submarine." Human Power. Fall 1993, Vol 10, No 4: 15—16.

Davidson, LCDR W. A. "The Spirit of Annapolis: Preparing for the Human-Powered Submarine Races." Human Power. Fall 1993, Vol 10, No 4: 17-19.

Besterfield, Glen H. and Wayne B. Paugh. "Cost Effective Fabrication of a Graphite/Epoxy Submarine

Hull." Human Power. Fall 1993, Vol 10, No 4: 19-23.

Poole, P.K. "H-P Submarines: Design Parameters." Human Power. Fall 1993, Vol 10, No 4: 24-26.

Ferry, Zachary, Devon Gaudet, Aaron Sutton, and Christopher Walker. University of Maine Human Powered Submarine. Final IHPS Report. University of Maine, 2006. Web. 1 Mar. 2013.

Orthmann, Alan. UW Human Powered Submarine. Prezi.com. University of Washington. Web. 1 Mar. 2013.

Australia. Department of Defence. Defence Science and Technology Organisation. Some Aspects of Submarine Design: Part 1. Hydrodynamics. By P. N. Joubert. Fishermans Bend, Victoria: DSTO Platform Sciences Laboratory, 2004. Web.

Australia. Department of Defence. Defence Science and Technology Organisation. Some Aspects of Submarine Design: Part 2. Shape of a Submarine. By P. N. Joubert. Fishermans Bend, Victoria: DSTO Platform Sciences Laboratory, 2006. Web.

"Second International Submarine Race Compilation of News Coverage." FAU College of Engineering and Computer Science, 1991. Web. http://vimeo.com/14587606

PROJECT MANAGEMENT

Rhine, Don. "The Engineering Design Process." 2008. Web. http://www.cs.uml.edu/teams-academy/index.php/ATDF2008/EDP

Canright, Shelley. "NASA Engineering Design Process." 2008. Web. http://www.nasa.gov/audience/foreducators/plantgrowth/reference/Eng_Design_5-12.htmlThe Engineering Design Process

FIBERGLASS

"SWEET COMPOSITES." -- FRP Materials & Supplies. Web. 20 Feb 2013.

"How To Use." How To Use. West System. Web. 22 March 2013.

"One-Off Construction Using Fiberglass Over Foam, An Overview of How to Work with Fiberglass Over Foam by Robert Q. Riley." One-Off Construction Using Fiberglass Over Foam. Web. 20 March 2013.

"Fiberglass Supply (Surfboards, Windsurfers, Kayaks, Canoes, Boats, Autos and More)." Fiberglass Supply (Surfboards, Windsurfers, Kayaks, Canoes, Boats, Autos and More). Web. 3 April 2013.

West System, Inc. West System User Manual & Product Guide. Bay City: West System, 2012. Print.

"Fiberglass Fabricators." Personal interview with Ray Rye. 21 Feb 2013.

"Sweet Composites." Personal interview. 18 March 2013 and 22 March 2013.

"Baltek." Personal interview. Various dates, 5-22 March 2013.

"Gurit." Personal interview. 5 and 7 March 2013

"Ferris Apiaries." Personal interview. 10 January 2013, 30 January 2013 and 14 March 2013.

ACRYLIC

Brown Bear, Kiki. "How to Oven Form Acrylic." Instructables.com. 17 Mar. 2009. Web. 27 Feb. 2013.

Plaskolite. Acrylic Forming. Plaskolite Inc., 2013. Web. 26 Apr. 2013.

Plaskolite. Plaskolite OPTIX Properties. Plaskolite Inc., 2013. Web. 26 Apr. 2013.

Syrillian. "Building and Modding with Acrylic: A Q&A." Online forum post. Building and Modding with Acrylic: A Q&A. 19 July 2008. Web. 28 Apr. 2013.

"Evonik." Personal interview.

"SpaceShipOne." - Smithsonian National Air and Space Museum. N.p., n.d. Web. 14 Mar. 2013.

"Precision Plastics." Personal interview. 14 March 2013

"SpaceShipOne." - Smithsonian National Air and Space Museum. Web. 14 Mar. 2013.

DIVE PLANES & LINKAGES

Huggett, Richard J. "Can I build a working Model Submarine?" The Association of Model Submariners. Web. http://associationofmodelsubmariners.com/can-i-build-a-working-model-submarine.php

"Airfoil Tools." http://airfoiltools.com/airfoil/details?airfoil=naca0008-il

"Rudder Construction." Stefan's Volksplane Construction Log. Web. http://www.stefanv.com/volksplane/rudder.html

"Wing Core Prototype." Manufacturing Details. University of Utah, Whale Watching. Web.

http://www.mech.utah.edu/senior_design/05/index.php/WhaleWatchingUAV/WingCorePrototype

"Compufoamcore." Web. http://www.compufoamcore.com

Friedman, Norman. US Submarines Since 1945: An Illustrated Design History. US Naval Institute. 1994 Web.

CUTTING CURED FIBERGLASS

Maier, Jim. Cutting Boat Fiberglass by Jim Maier. Web. https://www.youtube.com/watch?v=U_xi6FzKygY useful tips for cutting cured fiberglass.

UNIVERSITY OF MARYLAND

Department of Kinesiology
2351 School of Public Health Bldg
College Park, Maryland 20742-2611
301-405-2450 TEL
301-405-5578 FAX
www.sph.umd.edu/knes

Date: February 27, 2013

From: James Hagberg, PhD
Professor of Kinesiology and Medicine

To: Il Calamaro Human-Powered Submarine Team

Re: Results of VO_2max Laboratory Testing February, 2013

On Tuesday February 19, 2013 we completed two maximal oxygen consumption (VO_2max) tests on the proposed pilots for your human-powered submarine project. The goal of these tests was to assess the maximal ability of these two individuals to consume oxygen when they exercised at progressively increasing intensities until they were unable to continue because of generalized, musculoskeletal, and cardiorespiratory fatigue. These tests were conducted on a stairstepping ergometer to best simulate the muscular actions that are currently being proposed to power your submarine.

During exercise the human body and most mammals have evolved to utilize oxygen as their primary energy source, probably because of its substantial presence in our atmosphere and because the biochemical systems that have evolved to "burn" oxygen are very efficient compared to other energy sources. This type of metabolism is termed oxidative or aerobic metabolism and is assessed in exercise physiology laboratories as oxygen consumption (VO_2). The primary alternative energy system is glycolytic or anaerobic metabolism. While anaerobic metabolism works very well in a short burst of effort (say to evade a predatory animal back on the African plains), it is only about 5% as efficient as aerobic metabolism in terms of releasing the energy available in metabolic substrates. So long distance runners work virtually totally aerobically during their races, whereas 100 meter track sprinters rely virtually solely on their anaerobic metabolic systems. Bottom line is that you could run 100 meters holding your breath, but you could hardly do that for a marathon run!!!

In a VO_2max test our goal is to start the exercise at a moderate intensity relative to the capacity of the individual being tested and then to gradually increase the exercise intensity until the participant eventually cannot continue any further. We measure VO_2 during this test with a breathing apparatus that continuously measures the amount of expired air flow from the individual and the O_2 and CO_2 contents of the expired air. Using this information we can calculate the amount of O_2 that the participant is consuming during the exercise, their VO_2. VO_2max is expressed in two different units. The first is in "absolute" terms – the number of liters of O_2 consumed in a minute. This is probably the most useful value for your situation because it indicates the horsepower or joules that can be generated by the different pilots to propel your submarine. The second way of

1

expressing VO_2max is what we term the "relative" VO_2max because it is normalized per unit of body mass, in other words in units of milliliters of O_2 consumed per kilogram of body weight per minute. This value indicates how well a person could run long distances, which is probably not the most applicable number in your situation. During the test we also quantify a measure called the RER or respiratory exchange ratio. It is calculated as the volume of CO_2 produced divided by the volume of O_2 consumed. At the end of a VO_2max test the RER value is an index of the degree of hyperventilation that the participant is undergoing. This value helps us to determine if the test is actually a valid VO_2max test. The values for expired ventilation during the test should also be very useful for you in terms of the volume of compressed air that will need to be contained in the on-board supply tanks. We also assessed blood lactate levels in a blood sample from a finger prick approximately 4 minutes after the completion of the VO_2max test. This value also helps us to determine if the test was a true and valid VO_2max test. We also had the participants quantify their Rating of Perceived Exertion during each stage of the test to assess their perceptions of how hard they were working.

The tests on both Karl and Sam went virtually perfectly, although there was one slight treadmill malfunction late in Karl's test. There were essentially no technical issues during either test and, as is indicated below, both individuals gave excellent efforts with every measure we have available indicating that they went to their true maximal aerobic level of exertion, which is what is required for valid results in this test.

The results for the tests are presented in the table below.

Pilot	**Weight (kg)**	**Maximal Heart Rate**	**VO_2max, L/min**	**VO_2max, ml/kg/min**	**Maximal Ventilation**	**Maximal RER**	**Maximal Blood Lactate, mM/L**
Sam	88.6	193	4.1	39.5	140.5	1.19	18.9
Karl	85.9	200	4.34	50.7	143.3	1.06	7.0*

*blood sample taken well beyond 4 minutes after completion of exercise

To assess whether a true VO_2max has been achieved, at least 3 of the following criteria must be achieved: (1) a "leveling off" of VO_2 in the last stages of the test, (2) a heart rate in the expected range of maximal for that individual, (3) an RER exceeding 1.15, (4) a Rating of Perceived Exertion >18, and (5) a blood lactate level after exercise exceeding 8 mM/L.

In terms of "leveling off" of VO_2 in the last stages of the test, both tests clearly met this criterion as Sam's VO_2 was leveled off for the last 2+ minutes of the test and Karl's was leveled off for the last 2 ½ minutes of the test.

We estimate maximal heart rate from the equation 220 – age in years. Sam's measured maximal heart rate was within 10 beats/min of his predicted maximum and Karl's was 8 beats/min above his predicted maximal. These values provide further evidence of the true maximal nature of the tests.

An RER exceeding 1.15 at the end of a maximal exercise test is an indicator of a very high degree of hyperventilation, which is to be expected given the intensity of the final exercise stages. Sam's maximal RER clearly exceeded this criterion, while Karl's did not.

Both individuals had Ratings of Perceived Exertion (RPE) at the end of the test of 18 on a standard RPE scale of 6 to 20.

In terms of blood lactate levels after the test, Sam clearly exceeded the criterion value of 8 mM/L. While Karl's value was somewhat below that criterion level, his sample was taken substantially longer after the exercise than the desired 4 minutes. This in and of itself would result in a lower blood lactate level and he undoubtedly would have had a value exceeding 8 mM/L if the sample could have been obtained at the correct time.

Thus, both of these tests achieved at least 3 of these 5 criteria indicating that they were excellent, true, and valid VO_2max tests on both individuals.

I look forward to continue to interact with you on this project in terms of designing training programs for the two pilots to increase their power output to propel the submarine, to help to determine the amount of compressed air that must be carried in the on-board supply tanks, and any other physiological input that would assist your exciting efforts.

Once you have more information concerning the rules of the event related to how long the pilot will be on the on-board supply tanks and other such issues, please re-contact me and we can talk further about how to deal with these constraints.

Go Terps and Il Calamaro

CARTS INDEPENDENT

Il Calamaro

calamaro@qlubb.com