The *Turtle* Dives Again

At the beginning of the American Revolution, a man named David Bushnell developed the world's first practical submarine, which became known as the *Turtle*. He developed it in secrecy in Saybrook, Connecticut, and came tantalizingly close to sinking the flagship of the British fleet.

The *Turtle* was a round, bulky, awkward beast, about seven feet tall, roughly as long, and perhaps four feet wide. The inventor thought it looked like a pair of turtle shells joined together; a pilot thought it looked like a huge clam. It was not a craftsman's masterpiece. There was no fancy carving or polished brightwork; the whole thing was liberally coated in tar to waterproof the seams.

It was powered by two windmill-like screw propellers, a big one facing forward and a smaller, vertical one facing upward. The top of the boat was a tangle of pipes, valves and shafts congregating around a central brass cap that served as a hatch through which the pilot went in and out.

The *Turtle* attacked in a curious fashion: After maneuvering underneath an enemy ship, the operator speared its hull by cranking in a screw to which a large time bomb with a flintlock detonator was attached. The explosive device was what got Bushnell started with submarines in the first place; having invented a bomb that would work underwater, he came up with the submarine as a means of delivery.

Two centuries later, my partner Fredric Frese (a boatbuilder) and I (a photographer at the time) designed, built and tested a replica of this submarine. We launched our *Turtle* in the Connecticut River near Essex in the summer of 1977 and conducted a series of dives to find out what it must have been like to pilot Bushnell's craft.

In building the replica, we started looking at the submarine from Bushnell's perspective, not as historians but as boat builders. Once we put hammer to wood, we realized that we could have studied this thing forever without considering the important questions that Bushnell had to face. The major part of Bushnell's accomplishment was understanding the fundamental laws of physics and designing a device that could work in harmony with them. As historians, we never had to bother with these issues. As submarine builders, we had to make them our paramount concern.

Our first step was to assemble all the data we could find on the boat. It wasn't easy, because David Bushnell was secretive almost to the point of paranoia. No unnecessary person ever knew what he was doing; no contemporary drawings or paintings of the submarine are known to exist. There are no known likenesses of Bushnell himself either. The earliest letter about the submarine was written in Latin for confidentiality.

Although little source material survives, what we do have is of high quality. Bushnell wrote a pair of letters to Thomas Jefferson, including one four pages long that describes the *Turtle* in great detail. The craft's first combat pilot survived the war, and thirty years later wrote his recollections of the adventure. His account is extremely valuable because he alone tells us what it was like to operate the *Turtle* in action. We have only one witness to the events as they unfolded: Dr. Benjamin Gale, a gentleman scientist who lived in nearby Killingworth. Bushnell allowed Gale access to his project and relied on him to keep the Continental authorities informed. Gale's letters are full of important details, and they serve as the major source of information on the development of the *Turtle*.

These accounts tell of a dramatic and frustrating campaign. After building and testing the submarine in the summer and fall of 1775 (with support from Connecticut's Governor and Council of Safety), Bushnell trained his brother Ezra to operate it. When the Continental army moved to defend New York in the summer of 1776, Ezra took ill with a fever that was sweeping through General Washington's camp. A second pilot, a volunteer from the army named Ezra Lee, was hurriedly trained. On his first sortie, in early September, Lee succeeded in getting underneath Adm. Richard Howe's flagship, the *Eagle*, in New York Harbor, but he failed to deploy the submarine's weapon properly: He smacked the screw into the target but apparently hit an iron bracket supporting the rudder. (In later years, the story took hold that the ship's copper bottom thwarted Lee, but the participants agreed that he was stopped by iron and not copper, which the screw could have penetrated.) Pressing the screw against unyielding iron caused Lee and his *Turtle* to rebound from the ship.

He was unable to get back into the right position and decided to abort his mission. Hoping to distract the pursuing British, he cut the mine loose. It floated off into the East River, where it exploded with great violence shortly after dawn, to the wonder and alarm of the British navy and local civilians.

Bushnell tried a second attack a week or two later, a few miles up the Hudson at Fort Lee in New Jersey (across the river from Fort Washington, to which the beleaguered Continentals had withdrawn). This time the submarine dove too deep and was swept away by currents. A third attack was staged with a new pilot, probably Phineas Pratt, Bushnell's mechanic. He was challenged by an alert watch and barely managed to escape. The following morning a British squadron blasted past the rebel forts on the Hudson and sank the *Turtle's* mother ship, possibly called the *Crane*, taking the *Turtle* with it. Since the British saw the *Turtle* operating only on the surface, they never knew that they had been attacked by an underwater craft, never mentioned the new weapon in their logs, and apparently sank the revolutionary new boat without realizing what they had hit.

Bushnell continued his single-handed naval guerrilla war against the British by other means. He made further use of underwater explosives with a clever tethered mine that sank a British schooner near New London, Connecticut, and later with a barrage of floating mines at Philadelphia that British gunners had to pick off one by one. In 1779, he joined the Army's newly formed Corps of Sappers and Miners, eventually participating in the action at Yorktown. He spent most of the rest of his life as a teacher and physician in Georgia, where he died in 1826 at the age of eighty-five.

Unfortunately, few sources provide much hard information about the *Turtle*. Matters like how big, how heavy, how fast and how stable it was are open to interpretation. Over the years, many artists have drawn renditions, but as we began constructing our replica, we realized that few of these would actually work if they were faithfully built. Because the design of a submarine is tightly constrained, every design decision on one part affects components and systems elsewhere. The information in the historical record may be fragmentary, but by combining it with the laws of physics, we can learn a great deal about the nature of the world's first working submarine.

The first question to address in building a submarine is how to make it dive and return to the surface. Right away, there's a problem, because the submarine's wooden hull, the air captured inside, and the human operator are all buoyant. Even filling up the whole boat with water won't make it sink. The solution is to build a craft that can vary its weight to be either heavier or lighter than the water it displaces. (The relevant principles of buoyancy have been well known since ancient times, and were part of the curriculum at Yale in the early 1770s when Bushnell was a student there.)

We built our boat the same size and shape as Bushnell's was supposed to be and determined that it displaced 4,483 pounds of water. Allowing for the lack of exact specifications, we estimated that Bushnell's boat probably displaced between 4,000 and 4,500 pounds. The difference between that figure and the weight of the craft and pilot had to be made up with ballast.

Bushnell's hull was carved from huge sections of primary growth trees. Since we lacked access to these, we resorted to creating a rib structure and laying three-quarter inch-planks over it. Our hull and operator together weighed just over 900 pounds. Therefore, to get the thing to sink, we had to add more than 3,500 pounds. Most of this - about 2,100 pounds - was in the form of lead ingots placed on the floor of the sub. We also had 380 pounds of lead shot that could be dropped in as needed. Another huge ingot, more than 400 pounds, was fastened to the keel of the boat as a safety measure. It was attached to a chain and could be used as an anchor or released in an emergency to make the vessel light enough to pop to the surface.

The historical accounts give no displacement figures for the original *Turtle*, but Bushnell said that he used only 900 pounds of ballast, 200 of it in the form of an ingot attached to a chain. Ezra Lee's recollections contain similar numbers. After we had hammered our craft together, it seemed to us that 900 pounds of lead would hardly submerge a good size beach ball. The discrepancy between our figure and Bushnell's must have been due to the difference in weight between our relatively light planked hull and his heavy carved one.

The lead ballast brought both submarines close to the weight of the water they displaced but still left them light enough to float. Most of the *Turtle's* travel took place on the surface. When the time came to dive, the pilot would open a valve that allowed water to rush into the bottom of the cabin, thus making the boat heavy enough to submerge. To return to the surface, the pilot used a pair of hand pumps to expel the water. (We used the oldest pumps we could afford; they were similar in size and operation to the ones in Bushnell's craft.) We found that 11 cubic feet of water, weighing about 680 pounds, was enough to make our boat dive.

The volume of a submarine that rides above the water when its ballast tanks are empty is called its reserve buoyancy. To submerge, the reserve buoyancy must be overcome by an equal volume of water. If you build a submarine with a conning tower larger than its ballast tank, for example, the boat will never dive. We estimated that Bushnell's sub had to extend a foot or so out of the water to be safe from a passing wake or wave. Given his craft's dimensions, then, we think that our figure of 11 cubic feet must have been pretty close to the reserve buoyancy of the original *Turtle*.

Taking into account Bushnell's 900 pounds of lead ballast, this means that his wooden hull had to weigh somewhere around 2,500 pounds. This estimate is consistent with the few records we have. A 1775 letter from Samuel Osgood, a Massachusetts army captain who later became Postmaster General, to John Adams says that "its Weight is about a Tun." A footnote to Lee's 1815 account says that "its sides were at least six inches thick;" this would make for a boat weighing about 2,500 pounds. In the end, our submarine weighed about the same as Bushnell's; it's just that most of his sub's weight was wood and most of ours was lead.

Diving our *Turtle* was a memorable experience. Even with the flood valve full open, it took a long time for the boat to start going down. After opening the valve, I felt that I sat there wallowing on the surface for what seemed like forever. Then, as the water came up to the hatch, everything started to go faster. The windows of the *Turtle* are close to the operator's head, and you can look up and watch the water cover the skylights. The feeling of being swallowed up by the seas is inescapable. What a leap of faith it must have taken to dive in Bushnell's submarine!

The most important lesson we learned from our series of dives was that the *Turtle* was not a forgiving boat. Small difficulties could turn into big ones if not addressed immediately. For example, while the *Turtle* was quite maneuverable and responsive once in motion, it also had considerable inertia, making it tough to slow down or stop. If it submerged quickly, inertia would continue to drive it down even if I started emptying the ballast water immediately. Overcontrolling the dive and "porpoising" (oscillating) in depth was a very real problem. It took experience and judgment to close the valve at the earliest moment when negative buoyancy was achieved.

Currents and tides affected the boat strongly. Even when I cranked as hard as I could, the sub's propellers were often unable to counteract a river's flow or a harbor's tides. In these situations, it was essential to limit operations to the upstream side of the target. I quickly came to understand Ezra Lee's difficulties with the tides in New York harbor. One day the tide started to pull me out before I got back to the pier. I pointed the bow at the dock and cranked as hard as I could. Although I was on the surface at the time, I made very little progress. Fortunately, a rowboat came out, and easily pulled me back. If it hadn't been there, I would have had to run it aground and wait for slack tide. In a combat situation, this could have been fatal.

The *Turtle's* range is limited by its air capacity. In a sense, air is the boat's fuel. Bushnell claimed thirty minutes submerged in a letter to Jefferson, and Gale wrote that he could go "45 minutes without any Inconveniency as to breathing." We found that endurance depended on our work output. In a normal dive, we had enough air for thirty to forty five minutes submerged before the craft became unpleasantly stuffy. If a lot of maneuvering and pumping was required, that could drop to twenty minutes. Reducing tasks increased the limit; but we guessed that endurance dives exceeding one hour would be possible.

After mastering the basics of submerging and maneuvering, the most important thing an operator had to learn was how to find neutral buoyancy - the state of equilibrium at which the submarine is neither ascending nor descending. At true neutral buoyancy the boat hovers at the desired depth, feels light as a feather, and responds easily to the propeller and the tiller. The problem, we learned, was that this equilibrium was very hard to achieve and maintain.

Based on my experiences diving the submarine, I decided that the *Turtle* probably was not capable of attaining absolute neutral buoyancy. The two hand pumps were just too coarse for the kind of ballast control we needed, and the depth gauge – a simple glass tube closed at the top and open to the sea at the bottom - was not very accurate, so even if you were close to motionless, you couldn't be sure. It was maddeningly difficult to estimate depth or vertical speed; I found I was paying more attention to the depth than to anything else. I don't think I ever really nailed neutral buoyancy; at best I could maintain a gradual ascent or descent.

The vertical propeller was designed to assist in depth keeping, but I found it had no effect at all. Although we reproduced it faithfully from the descriptions in our sources, it never seemed to work. I spent a great deal of time at the bottom of a swimming pool and in the river furiously cranking the handle, but it soon became clear that all that cranking was taking me nowhere. Looking back long after the fact, I find it hard to believe that I ever thought it could work. There is simply no way a human could generate enough lift from such a small prop on such a heavy boat. And in fact Bushnell and Lee seem to equivocate in their writings about how useful the propeller really was.

All power on board the *Turtle* was provided by human muscle. While cranking on my two propellers, swinging the tiller, toiling away at the pumps and operating the attack system, I learned something very important about early submarining: a human working in a closed space changes the nature of the atmosphere.

First of all, with every breath he takes, the operator consumes oxygen and replaces it with carbon dioxide and water. When the proportion of carbon dioxide approaches 8 percent, breathing gets more labored, and any physical effort results in exhaustion. Between perspiration and respiration, the operator also adds a lot of water vapor to the warm air very quickly. The sides of the boat are chilled by the sea, so water vapor condenses all over the hull - on the walls, on the windows, and even overhead inside the hatch. In effect, the operator experiences an indoor underwater rainstorm.

The humidity was no big deal, since our boat leaked like crazy anyway. Although Bushnell's was built somewhat differently, I'm certain that it leaked too. The main problem from the humidity came when I tried to look out the windows. They would fog over again before I could finish wiping them off. We had divers accompanying the submarine, and they often complained that they could not see me because of the condensation.

Depleting the oxygen, flooding the air with carbon dioxide, and filling the atmosphere with water vapor is bound to make breathing difficult, but there is another process going on that makes it tougher still. From the moment the pilot closes himself off from the outside, the air pressure in the cabin begins to increase. As the pilot's body heat warms up the chamber, the pressure of the trapped air rises proportionally.

You start to feel a little pinching in the sinus and pressure on the ears. It gets worse the deeper you go and the harder you work. If you don't start pumping out the boat while there was plenty of air left, the result can be agony. It quickly gets to the point where you feel as if you have breathed every molecule in the boat's atmosphere several times over. There is a gasping, frightening feeling that the air might not hold out long enough to get you back to the surface. The pressure in your ears becomes a pounding headache. As more and more of the air gets used up, your breathing gets more rapid. Inhaling deeply brings no relief to the tightness in your chest.

Even when a dive was well controlled, with the air properly conserved and no excess water taken on board, pumping the submarine back to the surface was always an unpleasant chore. With a pump on each side, your arms swing up and down in a mechanical seesaw cadence; stroke after countless stroke, each one lightening the boat by no more than a pound or so. Hundreds of pounds have to be pumped out this way.

To a pilot, the big emotional moment is when the skylights finally struggle into the sunshine. While you are underwater, the surface seems impossibly far away, and suffocating a very distinct possibility. When the hatch clears, the drama is no longer life-threatening; fresh air is close at hand. Plenty of work remains, because further pumping is needed to lift the boat high enough for the operator to get out, but there is no longer the risk of death.

On the surface, observers could always tell when we had had a rough dive. As soon as the airpipes cleared the water, a valve disengaged and the high pressure inside the boat equalized with the lower pressure outside. The result was a violent belch of air out of the pipes. It made a whistling sound, sort of like blowing over the lip of a bottle. When the whistle lasted more than a second or so, it was clear the pilot had been through a lot.

Forces like wind, waves, currents and tides all combine to make a ship pitch, yaw and roll in predictable ways. In Bushnell's day the construction of stable sailing ships with pleasant handling characteristics was an intuitive art practiced by skilled and experienced craftsmen. A floating submarine is not that much different from a regular boat, so Bushnell was able to apply some lessons from shipbuilding in designing his craft.

The distribution of weight in a boat largely determines how it will handle in a rough sea. For a submarine to sit upright in the water, its center of gravity must be as far down as possible. This is accomplished by placing most of the weight low in the hull. Conversely, the center of buoyancy (that is, the center of gravity of the water displaced by the submarine) needs to be as high in the boat as is possible. If the center of buoyancy is significantly higher than the center of gravity, the boat will tend to be stable. A submarine with good stability rolls into a turn like a motorcycle. One with poor stability rolls uncomfortably away from the turn, wallowing like a drunken sailor.

In our *Turtle*, the center of buoyancy was only 15 inches above the center of gravity. This didn't matter much, because we operated it only in a very narrow range of speeds and wave heights. The original was designed for use in fairly calm harbor conditions, so this restriction made sense. Stability problems generally get worse with increased speed, but since the *Turtle* moved only about as fast as its name suggests, no troublesome conditions ever came up for us.

Bushnell probably had a greater problem with stability. The thick oak hull brought his center of gravity higher in the hull than ours, since less of the weight was sitting at the bottom as ballast. We partially simulated Bushnell's center of gravity by placing 2,100 of our 2,900 pounds of lead on the cabin floor, more than two feet up from the bottom of the submarine. Still, I suspect that his boat had it worse than ours. It probably rocked from side to side in tight turns, and felt pretty sloppy in a rough chop.

Unless it was racing a glacier or continental drift, the *Turtle* would never win a prize for speed. There is more conjecture than data on the subject of how fast it could go. Bushnell and his associates generally agreed that the submarine could crank out three knots. I'm pretty sure our *Turtle* never even did half that.

The top speed of a vessel is a function, in part, of the length of its hull. Generally, a longer boat will go faster than a shorter one. One common formula for displacement hulls like the *Turtle's* is that the maximum speed in knots, given an unlimited power supply, is equal to approximately 1.34 times the square root of the waterline length in feet. Calling the *Turtle* seven feet long, we find that it could have gone no faster than about three and a half knots.

In a human powered boat the speed obviously depends on the operator's strength and endurance. Rough calculations suggest that keeping the boat at two knots would require more horsepower than any human could put out. Although I'm willing to admit that Ezra Lee was a finer physical specimen than I am, I still can't imagine anyone making more than a knot or two. I doubt the *Turtle* ever left a noticeable wake. It is virtually impossible to tell the difference between two knots and three knots without actually measuring, especially with the restricted view you get from the top of a mostly submerged sub. We made guesses, but we never thought to measure our *Turtle's* top speed. It simply didn't go fast enough to warrant that.

After our brief series of test dives, we retired the *Turtle* to the Connecticut River Museum at Steamboat Dock in Essex, Connecticut. Because Bushnell built and tested his submarine in the Connecticut River, Fred and I felt it would be an appropriate place to keep it.

It has remained at Steamboat Dock since 1978, except for a one-year hiatus in 1986 during the opening of New London's *Nautilus* Museum. At the end of the year, the *Nautilus* museum commissioned Fred to build them a half-scale model of the *Turtle*. Since this one was never going to dive, Fred made it as a cutaway and was better able to replicate the 18th Century look and feel of the original.

The diving career of our *Turtle* is over. Its hull has dried out and some of its planks are coming apart. The pump leathers would have to be replaced, and the lead ballast is all gone; most of it was distributed to the divers who helped us. Although it will live out its days solely as a historical artifact, the *Turtle* exceeded expectations as a tool to understand Bushnell's experiences and achievements.

Hand-cranked submarines recently returned to the news with the announcement that the wreck of the Confederate submarine *Hunley* had been discovered off Charleston, South Carolina. The differences between the two submarines are ironic. The *Hunley* sank an enemy ship while the *Turtle* never did. The *Hunley* killed three of its own crews in attacks or training missions, while nobody was ever hurt in or by the *Turtle*. The *Hunley* succeeded as a weapon but failed as a submarine; the *Turtle* succeeded as a submarine but failed as a weapon.

The *Turtle's* success as a submarine is overshadowed by its misfortune in never sinking a British warship. Still, Bushnell succeeded in the same way as the Wright brothers did with their *Flyer* of 1903. Both craft left the surface of the earth, maneuvered independently, and returned safely. Both demonstrated a radical new technology upon which later innovators would expand.

In the *Turtle*, Bushnell was able to dive and change his course or depth underwater. After centuries of diving bells, the *Turtle* was finally free of the string - it was not tied to the surface by a tether or an air hose or an excess of buoyancy. It went wherever the operator caused it to go. Humble as it may have seemed, there in the murky waters of the Connecticut River, the *Turtle* was probably the first vehicle in human history to truly operate in three dimensions.

More than two centuries later, military submarines are keeping our sea-lanes open and deterring potential enemies. At Disneyworld, a fleet of *Nautilus*-style boats is operated in the popular "20,000 Leagues Under The Sea" ride. In the Caribbean, Hawaii and an increasing number of other tourist spots, visitors can study undersea life in absolute comfort in *Atlantis*-class passenger submarines. Elsewhere, research submarines from the venerable *Alvin* to brand-new boats that can dive to twenty thousand feet are exploring the geology and biology of the deep oceans. Their careers have been so dramatic that it seems hard to make a dive in one of them without discovering something radically new. All these vessels trace their ancestry back to the shadowy David Bushnell and his remarkable little machine.

To Bushnell a submarine was simply a delivery device, a way of getting his important invention, the underwater explosive, onto the underside of a British ship. After his first setback, he abandoned the idea of submarines and turned to other technologies to deliver his bombs. When those ideas failed, he went on to entirely different pursuits. Thus David Bushnell created the world's first practical submarine and then discarded the whole idea as impractical. It may have been the only real error in his engineering career.