Diving the USS Barometer

Diver Shayne Pemberton of Richardson, Texas, was messing around in his turtle pond. He filled a jar with water, raised the closed end above the surface of the pond, and a fish swam up into the jar. This got him thinking. What if the jar were 10 feet (3 meters) in diameter, 60 feet (18 m) long and filled with sea water? Suppose the open end were under water and the closed end above sea level. What would be the pressure at sea level inside the jar? What would happen if a diver swam up into the jar?

A jar of water 60 feet tall is like a mercury barometer used to measure atmospheric pressure. The actual barometer is a glass tube about a quarter of an inch (6.35mm) in diameter, filled with mercury with its open end inverted in a small pool of mercury.

The mercury in the upper end of the tube falls away from its sealed top by about an inch and hangs there at a height of about 30 inches (76 cm) above the surface of the mercury pool. The length of the column is equivalent to a pressure – the atmospheric or barometric pressure – 14.7 pounds per square inch absolute (psia). If a storm passes through or the barometer is carried up a mountain (that's what the "natural philosophers" did during the 1600s), the height of the mercury column falls as the barometric pressure drops.

The mercury column stands above the pool of mercury because the atmospheric pressure on the surface of the pool pushes it up the tube. The "empty" headspace at the top is really filled with mercury vapor.

To illustrate this point, you could make a barometer with sea water instead of mercury (avoid physical contact with mercury, as it is toxic). If the closed end of a seawater-filled tube were gradually raised above sea level, it would remain completely filled with water until the height reached 33 feet (10 m). Above this height, the sea water would pull away from the end of the tube, hang at 33 feet and would rise no further, no matter how high the tube was raised. If the tube were large enough to dive in, a diver would note that the pressure decreased as he or she ascended.

This works exactly the same way as in the mercury barometer, except that the liquid is water. In fact, freshwater barometers have been made, but instead of being 30 inches tall, they are 34 feet (11 m) tall – 34 feet of fresh water = 1 atmosphere pressure = 30 inches (76 cm) of mercury = 33 feet of sea water. The empty headspace at the top of the column is really water vapor at a pressure of 0.05 atmospheres absolute (ata).

The suction pump

A water barometer and a suction pump have much in common. If you open the headspace of the barometer to the atmosphere, the water falls back to sea level. Now close the headspace and apply a vacuum with a suction pump to draw sea water back up into the tube. The water will rise to 33 feet and stop. In a freshwater well, it is impossible to pump water from deeper than 34 feet for the same reason that water in a freshwater barometer won't rise higher than 34 feet – more about why this is so later.

Diving at altitude

What happened to the fish that swam up into the jar at Shayne Pemberton's turtle pond, and what would happen to a diver in a water barometer? First, we must remember that the pressure at sea level at the bottom of the water column is 1 ata, and the pressure in the headspace 33 feet higher up is 0.05 ata (the vapor pressure of water). If the diver swam up the water column to 16.5 feet (5 m), the absolute pressure would fall to half an atmosphere absolute (0.5 ata), equivalent to the barometric pressure at an altitude of

18,000 feet (5,486 m). If the diver swam up to 24 feet (7 m), the pressure would fall to 0.3 ata, equivalent to an altitude of 30,000 feet (9,144m). The top of Mt. Everest is about 29,000 feet (8,839 m), and an astronaut's space suit has a pressure equivalent to an altitude of 30,300 feet (9,235 m).

This diver is in an artificial world with two very unlikely diving problems. First, a diver breathing air at 24 feet in the water column will become unconscious from insufficient oxygen (hypoxia), because the oxygen partial pressure at 30,000 feet of altitude is only 0.06 atm or equivalent to 6 percent at sea level. To avoid hypoxia, an astronaut's space suit is filled with pure oxygen. Second, the diver will develop incapacitating or fatal altitude decompression sickness (DCS) as the nitrogen dissolved in his or her tissues becomes bubbles. To avoid DCS, astronauts breathe pure oxygen for up to four hours at sea level to eliminate dissolved nitrogen before they decompress to space suit pressure. Think about this artificial world: A column of compressible air more than 100,000 feet (330,480 m) tall was replaced with a 33-foot (10-m) tall column of incompressible sea water. Each column exerts the same weight on the surface of the ocean. Diving in a water barometer would be a clever way to teach both gauge and absolute pressures, except for hypoxia and DCS.

Boiling cold

Why is the column height in a seawater barometer limited to 33 feet, and why can't water be pumped up from wells deeper than 34 feet of fresh water? This is because of boiling. At room temperature – 72°F (22°C) – the water vapor pressure is 0.05 atm, or 0.7 psi. As water is heated, its vapor pressure rises, and when the temperature reaches 212°F (100°C), the vapor pressure is 14.7 psi, or 1 atm. Thus, water boils when its vapor pressure equals the absolute pressure. Think of it another way. When you ascend into the mountains, water boils at a lower (vapor) pressure because the barometric pressure is lower. The opposite is true in a pressure cooker, where you increase the pressure in the cooker to delay boiling until a higher temperature.

Decompression bubbles

There is a lesson here concerning bubbles that form during decompression. Bubbles form when the sum of all dissolved gas partial pressures (nitrogen, oxygen, carbon dioxide, helium, etc.) – plus the water vapor pressure – exceeds the absolute pressure. This is known as "supersaturation." During diving, however, and unlike boiling, the water vapor pressure is much lower than the dissolved nitrogen partial pressure, so nitrogen rather than water vapor drives bubble formation. Some decompression theorists argue that it is possible to withstand larger supersaturations before bubbles form in blood and tissue, but these excess supersaturations appear small if they exist at all. "Silent" bubbles that cause no DCS signs or symptoms can be present after all but trivial dives. Ultrasonic bubble detection routinely finds bubbles in humans at supersaturations as low as 0.4 atm (6 psi; 12 fsw/4 msw). Perhaps the large supersaturations in decompression theory represent silent bubbles that are too small or are in the wrong place to cause symptoms.

There is an even more exotic lesson concerning bubble formation: Water vapor will leave the water's surface only if there is an adjacent gas surface. If there were no gas surfaces in the water barometer, it would be possible to raise the water column to thousands of feet or meters in the air and have it stick right to the top. Strange as it might seem, the pressure at the top of the column would be hundreds of atmospheres less than atmospheric pressure. This has been demonstrated experimentally with very clean water and with superheated water that doesn't boil, even though the vapor pressure is hundreds of times greater than atmospheric pressure. When a bubble of pure water vapor finally does form, the water has reached its "tensile" strength and fractures or tears apart. This is known as de novo bubble formation, or bubbles forming “from nothing.” The reality is that bubbles practically always form from “something,” and that something is a small gas cavity whether it is in sea water or in us. Who says that physics has to be boring?

About the Author

Richard Vann joined the Duke Center for Diving Medicine and Environmental Physiology with a doctorate in biomedical engineering. He investigated bubble formation and inert gas exchange.
He developed decompression procedures used in scientific diving and by astronauts on EVAs from the Space Station.