Run for the Surface: An Application of Gas Laws

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Introduction/Teacher Notes: In this application, students will solve Boyle's Law problems and convert between units. This is the foundation for understanding gas laws, and sophisticated application and extension of the dimensional analysis methods used across physical science curricula. Students who complete this activity will be better able to link gas law theory and examples, and evaluate problems to decide if unit conversions are necessary. Practice in unit conversions will extend student experience in dimensional analysis.

Photo # NH 44576 USS Octopus surfacing during her preliminary trials, off Newport, R.I., July 1907

Standards: **Next Generation Science Standards**

HS-PS2-6. **Communicate scientific and technical information about why the molecular-level structure is important in the functioning of designed materials.**

HS-ETS1-2. **Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering.**

HS-ETS1-4. **Use a computer simulation to model the impact of proposed solutions to a complex real-world problem with numerous criteria and constraints on interactions within and between systems relevant to the problem.**

Common Core State Standards Connections:

ELA/Literacy -

RST.11-12.7 Integrate and evaluate multiple sources of information presented in diverse formats and media (e.g., quantitative data, video, multimedia) in order to address a question or solve a problem. (HS-PS2-1)

WHST.11-12.9 Draw evidence from informational texts to support analysis, reflection, and research. *(HS-PS2-1),(HS-PS2-5)*

Mathematics -

HSN.Q.A.1 Use units as a way to understand problems and to guide the solution of multi-step problems; choose and interpret units consistently in formulas; choose and interpret the scale and the origin in graphs and data displays. (HS-PS2-1),(HS-PS2-2),(HS-PS2-4),*(HS-PS2-5)*

HSA.SSE.A.1 Interpret expressions that represent a quantity in terms of its context. (HS-PS2-1),(HS-PS2-4)

HSA.CED.A.4 Rearrange formulas to highlight a quantity of interest, using the same reasoning as in solving equations. *(HS-PS2-1),(HS-PS2-2)*

Run for the Surface: An Application of Gas Laws

Background: Submarines are a marvel of science. A submarine controls its density with ballast tanks. These tanks can be filled with water or air as needed to alter the overall density of the ship for surfaced (air-filled) or submerged (water-filled) operation. Once submerged, internal variable ballast tanks are used to make minor adjustments to the ship's ballast, maintaining "neutral buoyancy".

When the main ballast tanks are filled with air when submerged, the volume of the air will change with changes in sea pressure. Deep in the water, sea pressure is higher and the air is compressed. As a submarine moves shallower, air in the ballast tanks will expand forcing out the sea water. This lowers the density of the submarine even more, accelerating the submarine upwards through the water.

Video, Normal Surfacing/Diving Process, ***Take 'Er Down (1954)*** https://www.youtube.com/watch?v=AaBu2IWNwWk&list=UUGiS44OoLuJJIiAWk341OAw

A submarine that needs to surface fast can do a procedure called an "emergency main ballast tank (EMBT) blow". In this maneuver, air stored in high pressure air banks is released to the ballast tanks. Ballast tanks are open to the ocean at the bottom, and closed with a vent valve at the top. Air in the ballast tank forces water out the bottom, because the air pressure is greater than the sea pressure.

> Teacher Note: In the video below, students will see a submarine breaching. An instructor can demonstrate this for students with a CO_2 cartridge gun, commonly used for blowing air to clean a computer. For a quick demonstration, fill a big 2-L beaker ¾ full of water. Fill a small beaker with water, and put it upside down in the large beaker, where it will sink to the bottom. Ask students what will happen when you fill the beaker with air – encourage students to recognize that the total density of the small beaker drops as the less dense air replaces the water it contains. Insert the straw of the air gun under the rim of the small beaker and fill it with a blast of air. The beaker will rise.

A video of a submarine doing an "emergency blow" shows the propulsive force of this procedure.

EMBT Blow Video: https://www.youtube.com/watch?v=ZMQDWDxHeXU

USS *Houston* (SSN 713) emergency surfaces during filming of “Hunt for Red October”

Normal Diving Process Video, ***Dive, Dive: “The Submariners” (1967)*** https://www.youtube.com/watch?v=E_tYb0ws66E&list=UUGiS44OoLuJJIiAWk341OAw

The Science: Chemists, like submariners, often work with changing volumes and pressures of gases. Boyle’s Law states that the pressure and volume of a gas at a constant temperature are inversely proportional. As pressure increases, volume shrinks. As pressure decreases, volume expands. Mathematically, this is represented as:

$$P_1V_1=P_2V_2$$

The units in this equation are not specified. Algebraic manipulation of this equation explains why.

A. **For example, solving for P_2** :

$$P_2 = P_1V_1/V_2$$

Given: P_1=4300 *psi*

V_1=2400 ft^3

V_2= 38000 ft^3

$$P2 = \frac{(4300\ psi)x(2400\ ft3)}{38000\ ft3}$$

Notice that the unit ft^3 crosses out in this equation. P_2 has the same unit in the end as P_1.

P_2= 271.58 *psi* , or 270 *psi* to two significant figures.

Evaluate this answer. Does it make sense? The volume increased dramatically. The pressure should have decreased – it did. The unit at the end is psi; this is a pressure unit, further evidence that our answer makes sense. ***This process of evaluating the answer is important for catching errors.***

B. Problemsolving Practice. Complete the following Boyle's law problems.

1. P_1 = 4300 *psi*
   V_1 = 2900 *ft3*
   V_2 = 32000 *ft3*
   Find P_2

2. On an average day, the air pressure at the surface is about 14.7 *psi*. For each 100 feet of depth, pressure increases by 44 *psi*. If a submarine has 450 *ft3* of air in a ballast tank at the surface, and descends to a depth of 500 feet, what is the volume of the air in that ballast tank?

3. At a depth of 650 feet, a submarine releases 1000 *ft3* of air into her ballast tank. What will the volume of that air be when the ship reaches the surface?

4. At a depth of 480 feet, a submarine releases air from one of its air banks. The original pressure in the air bank is 4400 *psi*. The air fills a volume of 18000 *ft3* at depth. At the surface, the air fills the ship's ballast tank with a volume of 31,700 *ft3*. What is the final pressure of the air in that air bank?

C. Problem Review. After completing these problems, work with a partner taking turns explaining why each answer makes sense. Follow the model for evaluating answers shown above.

D. Units! One challenge in transitioning from the environment of a submarine to that of land based science is that most labs and science classes use SI units instead of the English units psi and *ft3*.

1.000 *psi* = 6.895 *kPa*.
1.000 gallon = .13368 *ft3* = 3.7854 liters
1.00 meter of depth increases pressure by 9.98 *kPa*
Surface pressure = 101.3*kPa*

Convert each of the units in one of the above problems to SI units, and calculate the answer in SI units. Convert your answer from SI back to English units. Confirm that your answer is the same regardless of the units you were working in. Working with a partner who converted a different problem, demonstrate that the unit labels change, but that the answers still work out. **

E. **Application**. Solve the following problem. Watch your unit labels!

A submarine is at a depth of 520 feet. It releases 1400 *psi* of pressure from its 1820 cubic foot air banks, displacing 105,000 gallons of water from ballast tanks. What is the pressure at the surface of this air in *kPa*? What volume in liters will it fill? Create a clear set of calculations that you could use to demonstrate the solution to this problem.

Another Submarine & Diving Application, Breathing at High Pressure.

Boyle's Law has other applications for submariners, beyond the filling of ballast tanks for an emergency blow. Submarines make their own oxygen and scrub unwanted carbon dioxide from the atmosphere. It is the concentration and percent of oxygen in the air that determines the saturation level of oxygen in our bloodstream.

Maintaining appropriate concentrations and pressures of oxygen is an important job aboard a submarine, and knowledge of Boyle's Law is used daily. In the event an escape from a submarine should be necessary, understanding Boyle's Law is vital for survival. When a submariner exits a sunken ship at depth, the sea pressure is enormous. His/her lungs are filled with air at the intense pressure associated with that depth (44 *psi* per 100 ft) in order to escape safely from the submarine.

Watch the video linked below. Pay attention to the sailors' ascent!

https://www.youtube.com/watch?v=wd2Plax5HhI

- What do the sailors do as they rise through the water?

- Explain the importance of this behavior using Boyle's law.**

Teacher's Note: The point to notice in the submariner escape video of actual practice of an underwater escape, is that their biggest problem escaping from a submarine deep in the water is a Boyle's law problem. If the submariner holds his breath on the way up through the water, steadily declining pressure will increase the volume of air in his lungs. The lungs fill beyond capacity, with unpleasant results. In practice, the submariners yell "BooYaaaaaaaa!" expelling air all the way to the surface. They do not run out of air!!

More Science. One other change that happens as a submarine approaches the surface is that the temperature of the gas sample rises. Using what you know about the kinetic molecular theory (KMT), what effect do you think this change of temperature will have on the volume of the air? With your partner, work out an explanation of the effect of temperature on the gas volume, based on KMT.

More Gas Laws: In this activity on-line, students study gas laws at a molecular level. They vary the volume of a container at constant temperature to see how pressure changes (Boyle's Law), change the temperature of a container at constant pressure to see how the volume changes with temperature (Charles's Law), and experiment with heating a gas in a closed container to discover how pressure changes with temperature (Gay Lussac's Law). They also discover the relationship between the number of gas molecules and gas volume (Avogadro's Law). Finally, students use their knowledge of gas laws to model a heated soda can collapsing as it is plunged into ice water.

http://concord.org/stem-resources/gas-laws

Summary. Select one of the two ** items to write about. Explain your work in a way that is scientifically correct, with writing that is clear and grammatically correct.

Evaluate Understanding. To evaluate students' work, teachers may use a variety of methods. One simple way is to ask students to be prepared to present. Select students at random for each item in the document, put their work on a document camera, and ask them to explain their solutions. Alternately, the products could be part of a student's digital portfolio with each item carefully scored. Finally, a teacher might elect to evaluate student work using the holistic rubric below.

Extension/More Scaffolding Questions.

On the U.S. Navy's newest *Virginia* class submarines under construction at present, the ballast tank capacity is 31,705 cubic feet. The air banks consist of 4 tanks of 480 cubic feet each, held at a pressure of at least 4300 psi, with a maximum of around 4700 psi. Additional problems may be teacher developed to scaffold the skills here more slowly, using units, conversions, and Boyle's Law.

Holistic rubric for lesson evaluation:

	3	2	1
Each calculation is accurate	Significant figures and unit labels consistently correct	Values are correctly calculated, but there are some problems with units or sigfigs	Calculations are unclear or incorrect.
Verbal Explanations	Complete, scientifically correct, insightful	Scientifically correct, but some parts are incomplete or unclear	Explanations are not scientifically correct, or are too incomplete to be of value
Collaboration	Students are on task, working collaboratively to solve problems	With a little prodding, students are collaborating and on task	Repeated prompts are necessary to keep students on task
Written explanations	Complete, scientifically correct, well-written	Scientifically correct, but some parts are incomplete or writing needs improvement	Explanations are not scientifically correct, or are too poorly written to be of value