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The Problem

The greatest limiting factor in any underwater exertion is the performance of the breathing apparatus, otherwise known as the scuba regulator. The designer of underwater breathing apparatuses used by today's recreational, professional and commercial divers must consider the many types of loading imposed on humans underwater.

The underwater environment imposes many stressors, both physically and mentally, on those working in it. Movements in the underwater environment require a higher expenditure of energy and an increased rate of respiration than the same task or movement on land. This occurs due to the density of water and the need to overcome water resistance or drag (Pendergast et al., 2005). Pressure on a diver's airways, the drag of equipment through the water, and water movement (currents) are also physically demanding. Additional stressors include anxiety, visual changes, and a limited ability to communicate. The individual or combined affect of these stressors on the diver can cause an increased respiratory rate and demand for air. Inability to receive sufficient air, or a perceived "starving" for air, will lead to psychological or physical distress and may be life threatening in an underwater environment. Starving for air may lead to panic in which the diver may abandon his/her equipment or make other rash decisions, putting their life and the life of other divers at risk.

Breathing resistance is directly related to the diver's ability to receive sufficient air to safely perform in the underwater environment and must be considered a primary factor in the design of breathing apparatuses.

Physiology

Normal inhalation is achieved through the contraction of the diaphragm and muscles associated with the ribs and below the lungs. During inhalation, the chest cavity expands and pulls on the membrane (pleura) around the lungs enlarging them. This increase of the lung volume causes the pressure within the lungs to decrease, allowing air to flow into the lungs to equalize the pressure. When exhaling, the muscles and diaphragm relax, pushing the air out. The volume of air breathed in and out is referred to as the tidal volume. The average person's tidal volume at rest is approximately 0.5 liters (NOAA, 2001).

Vital capacity refers to the largest amount of air exhaled after maximum air has been inhaled. The volume of a person's vital capacity is dependant upon size, age, and health. Vital capacity does not necessarily affect a person's ability to work or exercise and may not affect supply of oxygen to the blood (Brylske et al., 1996).

In addition to the vital capacity, there is an inspiratory reserve and an expiratory reserve. Following a normal inhalation, the average person can forcefully inhale approximately three additional liters. Even after forcing compete exhalation, there remains about one liter of air in the lungs. This expiratory reserve, or residual volume, keeps the lungs from collapsing (NOAA, 2001).

The average person takes approximately 10-20 breaths per minute (Brylske et al., 1996). When a person begins light exercise, the tidal volume may increase and with heavier work the frequency of breaths will increase as well, often up to 45 breaths per minute (Kroemer, Kroemer, Kroemer-Elbert, 2001). A scuba diver however will take between 25-31 breaths per minute on a relaxing dive where no strenuous activity is encountered (Dive-Rite, 2006). Due to the increased respiration of a diver at rest, the equipment used must be designed to provide a sufficient air supply with minimal resistance.

Equipment

A self contained underwater breathing apparatus (scuba) is typically used by divers for breathing underwater. A scuba system employs a regulator, an air tank or cylinder, a depth gauge and a pressure gauge. In very simplistic terms, the regulator allows the diver to breath off the air contained in the cylinder while monitoring the remaining air with a pressure gauge and monitoring the diver's current depth on the depth gauge.

A scuba cylinder or tank is under high pressures. The typical scuba tank is pressurized to 3000psi (pounds per square inch). Human lungs cannot breathe air at such a high pressure without serious injury. Ambient air temperature at sea level is only 14.7psi. The primary function of the regulator is to reduce the high-pressure breathing gas contained in the air cylinder to the ambient pressure so the diver may breathe it (NOAA, 2001).

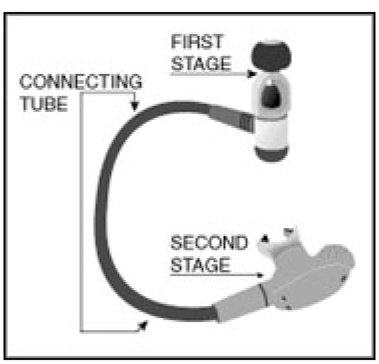


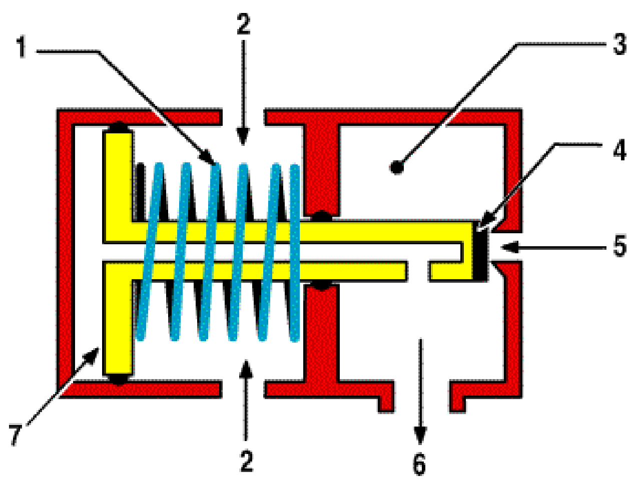
Figure1. The first & second stages of a regulator (Coris Glossary, 2006).

The first stage attaches to the cylinder. The second stage is held in the diver's mouth and delivers the air

The most commonly used type of regulator is the open circuit "demand" valve regulator. It is referred to as a demand regulator because it only supplies air when the diver inhales or "demands" it (NOAA, 2001). This type of regulator consists of two main components, referred to as the first and the second stages. The first stage attaches to the air cylinder and delivers air to the second stage which is held in the diver's mouth or provides air to the diver's mask (Figure 1). The first stage takes high pressure air from the cylinder and reduces it to an intermediate pressure. The intermediate pressure travels to the second stage and there is reduced to ambient pressure.

The breathing resistance experienced by the diver may be attributed to the design in either the first or second stages. There are two primary types of regulator first stages, piston and diaphragm. Each type can also be either balanced or unbalanced.

Figure 2. Unbalanced Piston Style Regulator First Stage (Regulators, 2006).



1. High Pressure spring
2. Ambient water pressure
3. Intermediate chamber
4. Valve and high pressure seat assembly
5. High pressure air
6. Air to second stage
7. First stage unbalanced piston

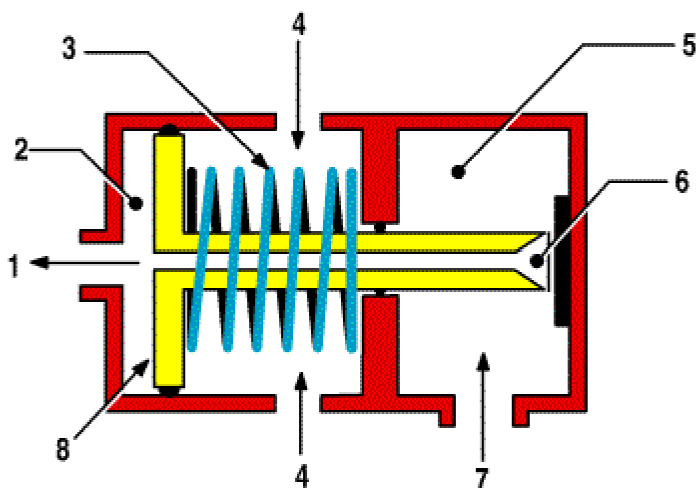
Unbalanced Piston Regulator First Stage

This first stage regulator works by using the opposing forces of the intermediate pressure and the high pressure spring in the regulator. When a diver demands air by inhaling, the intermediate pressure is lowered causing the main spring to move the piston towards the low pressure. The piston removes the valve off the seat, allowing air to enter from the tank. The entering air raises the pressure and causes the spring to move the piston back to the closed position (Regulators, 2006). When in the closed position, the regulator will not allow additional air from the tank to enter (Brylske et al., 1996).

Breathing resistance at depth will increase and breathing becomes more labored with the regulator design depicted in Figure 2. This occurs due to the regulator being unbalanced. The valve is affected by the pressure change in the air that is entering from the tank. As air is consumed by the diver, the air pressure in the cylinder decreases and the intermediate pressure in the valve rises. Because of the small orifice (seen above at # 5) where the high pressure air from the cylinder enters, airflow is decreased so much that breathing resistance is increased (Regulators, 2006).

Once the cylinder reaches approximately 1000psi, the diver will begin feeling the higher resistance in breathing. To compound this problem, cylinder pressure is lowest at the end of a dive when the diver may be fatigued or having difficulty making it to the point of exit such as a dock, beach or boat. While this type of valve will continue to give sufficient air to the diver, the loading psychologically due to the increased resistance of airflow can lead to diver distress or panic.

Figure 3. Balanced Piston Style Regulator First Stage (Regulators, 2006).



1. Air to second stage
2. Intermediate chamber
3. High pressure spring
4. Ambient water pressure
5. High pressure air chamber
6. Valve & high pressure seat
7. High pressure air
8. Balanced piston assembly

Balanced Piston Style Regulator First Stage
The primary difference between the balanced piston and the unbalanced piston is that the valve is not influenced by the high pressure air entering from the tank. This provides more consistent breathing resistance to the diver. The diver will usually be unaware of any difference in the drawing of a breath from the first to the last even with decreasing pressure in the cylinder.

Unbalanced Diaphragm Regulator First Stage
A diaphragm regulator is also referred to as an upstream first stage. The valve seat is located on the high pressure side of the valve (Figure 4). When the diver takes a breath, the diaphragm flexes inward and pushes a rod to open the valve. When the intermediate pressure increases to a predetermined point, the diaphragm relaxes and the valve is closed. This type of valve has a small opening (seen at #6) and will reduce

airflow as well as being unbalanced and therefore breathing resistance will increase as the cylinder pressure decreases (Regulators, 2006).

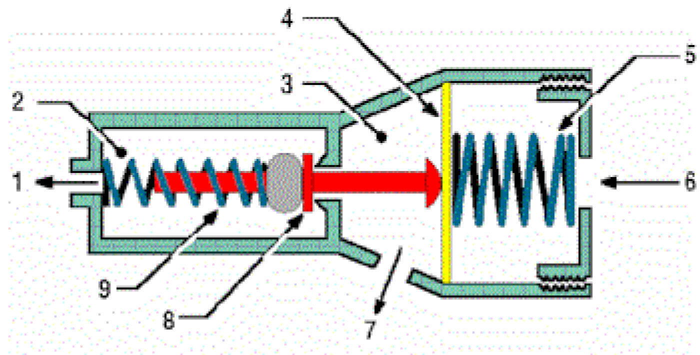
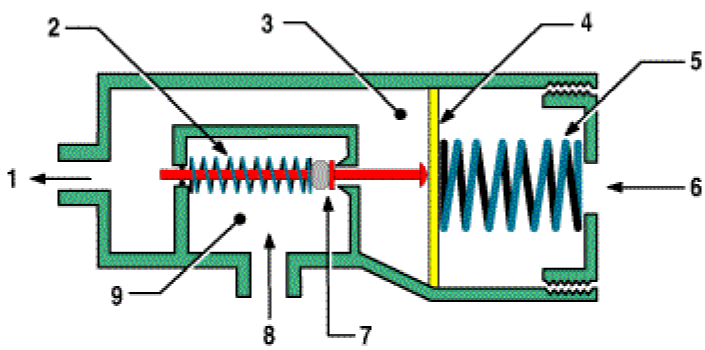


Figure 4. Unbalanced Diaphragm Regulator First Stage (Regulators, 2006).

1. High pressure air
2. High pressure air chamber
3. Intermediate chamber
4. Diaphragm
5. Diaphragm balance spring
6. Ambient water pressure
7. Air to second stage
8. Valve & HP seat assembly
9. High pressure spring

Balanced Diaphragm Regulator First Stage
This regulator operates in a very similar manner to the balanced piston regulator. The primary difference is that a diaphragm pushes the valve open to allow air to enter rather than a piston. Because of the valve stem extends through the high pressure chamber into the intermediate chamber, the air pressure in the cylinder cannot exert force on the valve stem (Figure 5). The air pressure in the cylinder will have no effect on the breathing resistance of the diver throughout the dive.

Figure 5. Balanced Diaphragm Regulator First Stage (Regulators, 2006).



1. Air to second stage
2. Valve balance spring
3. Intermediate chamber
4. Diaphragm
5. Balance spring
6. Ambient water pressure
7. Valve & HP seat assembly
8. HP air
9. HP air chamber

Regulator Second Stages
The second stage of a regulator is the portion the diver holds in their mouth. The second stage takes the intermediate pressure from the first stage and reduces the pressure further to the ambient air pressure so the diver may breathe without injury. The second stage includes a purge button to remove excess water from the unit and a mouthpiece placed between the diver's teeth to maintain its position.

When the diver inhales, the pressure inside the second stage decreases, causing a diaphragm to depress and actuate a lever. This lever opens the valve allowing air to come into the second stage and to the diver. When the diver exhales, the diaphragm is extended and the exhaled gas leaves the second stage through exhaust ports located at the bottom of the second stage (NOAA, 2001). The pressure needed to move the lever into the open position is called the cracking pressure. The lower the cracking pressure the less breathing resistance is felt by the diver.

Figure 6. Regulator Second Stage (Selecting a Regulator, 2006)

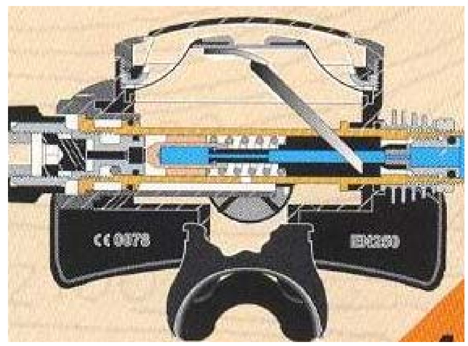
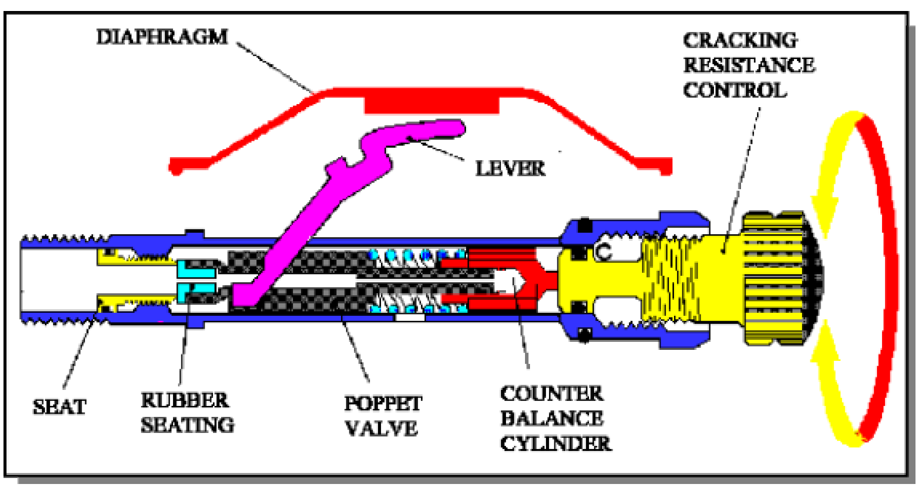


Figure 7 details the lever and diaphragm of a second stage. The knob to the right is used by the diver underwater to increase or decrease the pressure required to inhale. Opening this knob up at depth will lessen the cracking pressure.

Figure 7. Regulator Second Stage Assembly Detail (A Regulator Second Stage, 2006).



The design of the second stage may greatly effect the diver's breathing resistance. If the cracking pressure of the lever upon inhalation is too high, the diver will experience a feeling of air starvation. A malfunctioning second stage may also increase the resistance felt by the diver to exhale. Although this is a rare occurrence, a high resistance in exhaling can cause significant stress and loading underwater. Studies have shown however that the inspiratory resistance does indeed outweigh the expiratory resistance in a diver's ability to perform underwater (Warkander, Nagasawa, Lundgren, 2001).

Performance Testing of Underwater Breathing Apparatuses

Regulators are tested using the National Agency for Science, Technology and Innovation (ANTSI) testing system. This system evaluates regulators on human breathing simulation, scientific repeatability, test time, and complexity. Regulators are tested at several different breathing rates thus testing the regulator at different tidal volumes as well. The different breathing rates and volume are referred to as the RMV or respiratory minute volume. This RMV is measured in liters per minute (How Regulator Testing Works, 2006). The amount of energy expended by a diver is measured in joules per liter, known as the work of breathing or WOB.

Each manufacturer or institution will test a regulator at their own chosen RMV. The results are generally compared to the goal set by the US Navy. The Navy prefers regulators that perform with a work of breathing at "1.3 j/l or less when breathed at 62.5 RMV at both 132 fsw (feet in salt water) and at 198 fsw using a 1500 psig supply pressure (How Regulator Testing Works, 2006)." Figure 8 shows a sample results page for a balanced first and second stage regulator tested with the ANSTI system.

Figure 8. Results from ANSTI Testing of a Scuba Regulator (Zeagle, 2006).

DEMAND REGULATOR PERFORMANCE

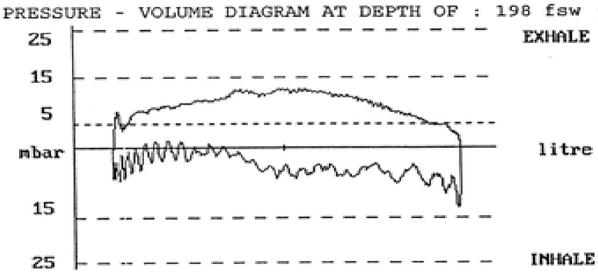
— ANSTI — DIVE LAB — ANSTI —
CERTIFICATE REFERENCE : DL 0306 1 4261
DATE : 06-25-2005 TIME : 15:17:27

EQUIPMENT
REGULATOR TYPE : ZEAGLE DS-V
SERIAL NUMBER : 1ST A001662 2ND H007692
INTERMEDIATE PRESSURE : 132 psig(9.1 barg) SURFACE/STATIC

CONDITIONS OF TEST
ROOM TEMPERATURE : 0.0 F (%-17.8 C)
WATER TEMPERATURE : 51.1 F (10.6 C)
EXHALE TEMPERATURE : 57.9 F (14.4 C)
HP SUPPLY PRESSURE : 742 psig (51.2 barg)
TIDAL VOLUME : 2.50 litre BREATH RATE : 25.03 bpm
VENTILATION RATE : 62.6 lpm

RESULTS
INHALE PRESSURE = 12.77 mbar
INHALE POS PRESSURE = 1.38 mbar
EXHALE PRESSURE = 12.60 mbar
EXT WORK OF BREATHING = 1.09 J/l
INHALE WORK = 0.39 J/l
POS INHALE WORK = 0.00 J/l
EXHALE WORK = 0.90 J/l

PRESSURE - VOLUME DIAGRAM AT DEPTH OF : 198 fsw (60.3 msw)



Solution

The solution to the adverse effects of additional loading caused by increased breathing resistance in an underwater environment is to use a balanced regulator. In contrast to unbalanced regulators, balanced regulators will maintain a consistent breathing resistance throughout the dive regardless of decreasing pressure in the scuba tank. In addition, a balanced regulator that requires no more than the US Navy's goal of 1.3 j/l is highly recommended and is readily available in today's market.

A high performing, balanced regulator will reduce the physiological and psychological stressors encountered in the underwater environment, providing safer diving for individuals and their fellow divers.

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