1. Details of Module and its structure

Module Detail	
Subject Name	Physics
Course Name	Physics 02 (Physics Part 2, Class XI)
Module Name/Title	Unit 7, Module 4, Bulk Modulus of Elasticity Chapter 9, Mechanical properties of solids
Module Id	Keph_20904_eContent
Pre-requisites	Rigid body, internal structure of solids, inter-atomic forces, elasticity, longitudinal stress and longitudinal strain, young's modulus of elasticity, Searle's apparatus and its application. Load extension graph.
Objectives	After going through this lesson, the learners will be able to: • Understand the meaning of Volumetric strain • Visualize Volumetric stress due to Hydrostatic deforming pressure • Derive an expression for Bulk Modulus K, justify, why negative sign is introduced in the formula of K • Apply volumetric strain to realise behaviour of Fish, and other deep sea aquatic life • Explain the need for deep sea diver suits and special material for submarines
Keywords	Volumetric stress , volumetric strain ,bulk modulus of elasticity,

2. Development Team

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1. UNIT SYLLABUS

UNIT 7: PROPERTIES OF BULK MATTER: 24 periods

Syllabus

Chapter–9: Mechanical Properties of Solids:

Elastic behaviour, Stress-strain relationship, Hooke's law, Young's modulus, bulk modulus, shear, modulus of rigidity, Poisson's ratio, elastic energy.

Chapter–10: Mechanical Properties of Fluids:

Pressure due to a fluid column; Pascal's law and its applications(hydraulic lift and hydraulic brakes). Effect of gravity on fluid pressure. Viscosity, Stokes' law, terminal velocity, streamline and turbulent flow, critical velocity, Bernoulli's theorem and its applications. Surface energy and surface tension, angle of contact, excess of pressure across a curved surface, application of surface tension ideas to drops, bubbles and capillary rise

Chapter–11: Thermal Properties of Matter:

Heat, temperature, thermal expansion; thermal expansion of solids, liquids and gases, anomalous expansion of water; specific heat capacity; Cp, Cv - calorimetry; change of state - latent heat capacity. Heat transfer-conduction, convection and radiation, thermal conductivity, qualitative ideas of Blackbody radiation, Wien's displacement Law, Stefan's law, Greenhouse effect.

2. MODULE-WISE DISTRIBUTION OF UNIT SYLLABUS 17 MODULES

Module 1	• **Forces between atoms and molecules making up the bulk matter** • **Reasons to believe that intermolecular and interatomic forces exist** • **Overview of unit**

	• State of matter • Study of a few selected properties of matter • Study of elastic behaviour of solids • Stationary fluid property: pressure and viscosity • Stationary liquid property: surface tension • Properties of Flowing fluids • Effect of heat on matter
Module 2	• Idea of deformation by external force • Elastic nature of materials • Elastic behaviour • Plastic behaviour • Tensile stress • Longitudinal Stress and longitudinal strain • Relation between stress and strain • Hooke's law • Young's modulus of elasticity 'Y'
Module 3	• Searle's apparatus • Experiment to determine Young's modulus of the material of a wire in the laboratory • What do we learn from the experiment?
Module 4	• Volumetric strain • Volumetric stress • Hydraulic stress • Bulk modulus K • Fish, aquatic life on seabed, deep sea diver suits and submarines
Module 5	• Shear strain • Shear stress • Modulus of Rigidity G • Poisson's ratio • Elastic energy • To study the effect of load on depression of a suitably clamped meter scale loaded at i)its ends ii)in the middle • Height of sand heaps , height of mountains
Module 6	• Fluids-liquids and gases • Stationary and flowing fluids • Pressure due to a fluid column • Pressure exerted by solid , liquids and gases • Direction of Pressure exerted by solids, liquids and gases

Module 7	• Viscosity- coefficient of viscosity • Stokes' Law • Terminal velocity • Examples • Determine the coefficient of viscosity of a given viscous liquid by measuring terminal velocity of a given spherical body in the laboratory
Module 8	• Streamline and turbulent flow • Critical velocity • Reynolds number • Obtaining the Reynolds number formula using method of dimensions • Need for Reynolds number and factors effecting its value • Equation of continuity for fluid flow • Examples
Module 9	• Bernoulli's theorem • To observe the decrease in pressure with increase in velocity of a fluid • Magnus effect • Applications of Bernoulli's theorem • Examples • Doppler test for blockage in arteries
Module 10	• Liquid surface • Surface energy • Surface tension defined through force and through energy • Angle of contact • Measuring surface tension
Module 11	• Effects of surface tension in daily life • Excess pressure across a curved liquid surface • Application of surface tension to drops, bubbles • Capillarity • Determination of surface tension of water by capillary rise method in the laboratory • To study the effect of detergent on surface tension of water through observations on capillary rise.
Module 12	• Thermal properties of matter • Heat • Temperature • Thermometers

Module 13	• **Thermal expansion** • **To observe and explain the effect of heating on a bi-metallic strip** • **Practical applications of bimetallic strips** • **Expansion of solids, liquids and gases** • **To note the change in the level of liquid in a container on heating and to interpret the results** • **Anomalous expansion of water**
Module 14	• **Rise in temperature** • **Heat capacity of a body** • **Specific heat capacity of a material** • **Calorimetry** • **To determine specific heat capacity of a given solid material by the method of mixtures** • **Heat capacities of a gas have a large range** • **Specific heat at constant volume C_V** • **Specific heat capacity at constant pressure C_P**
Module 15	• **Change of state** • **To observe change of state and plot a cooling curve for molten wax.** • **Melting point, Regelation, Evaporation, boiling point, sublimation** • **Triple point of water** • **Latent heat of fusion** • **Latent heat of vaporisation** • **Calorimetry and determination of specific latent heat capacity**
Module 16	• **Heat Transfer** • **Conduction, convection, radiation** • **Coefficient of thermal conductivity** • **Convection**
Module 17	• **Black body** • **Black body radiation** • **Wien’s displacement law** • **Stefan’s law** • **Newton’s law of cooling,** • **To study the temperature, time relation for a hot body by plotting its cooling curve** • **To study the factors affecting the rate of loss of heat of a liquid** • **Greenhouse effect**

3. WORDS YOU MUST KNOW

- **Rigid body:** is a solid body in which deformation is zero or so small it can be neglected. The distance between any two given points on a rigid body remains constant in time regardless of external forces exerted on it. A rigid body is usually considered as a continuous distribution of mass.
- **Interatomic forces:** are the **forces** which mediate interaction between molecules, including **forces** of attraction or repulsion which act between molecules and other types of neighbouring particles, e.g., atoms or ions.

- **Internal structure of Solid:**

Crystalline solid: is a **solid** material whose constituents (such as atoms, molecules, or ions) are arranged in a highly ordered microscopic structure, forming a crystal lattice that extends in all directions.

Lattice: Ionic compounds are made up of ions - positive and negatively charged particles. These positive and negative ions attract each other and group together in giant structures called lattices. In the lattice, each positive ion is surrounded by several negative ions.

Bond length: In molecular geometry, *bond length* or *bond* distance is the average distance between nuclei of two bonded atoms in a molecule. It is a transferable property of a ***bond*** between atoms of fixed types, relatively independent of the rest of the molecule.

- **Bond energy:** *bond energy* (E) or *bond* enthalpy (H) is the measure of *bond* strength in a chemical *bond*.
- **Amorphous solid:** or non-crystalline *solid* is a *solid* that lacks the long-range order that is characteristic of a crystal. In some older books, the term has been used synonymously with glass.

- **Molecular structure of Liquid:** A **liquid** is a nearly incompressible fluid that conforms to the shape of its container but retains a (nearly) constant volume independent of pressure. As such, it is one of the four fundamental states of matter (the others being solid, gas, and plasma), and is the only state with a definite volume but no fixed shape. A liquid is made up of tiny vibrating particles of matter, such as atoms, held together by intermolecular bonds.

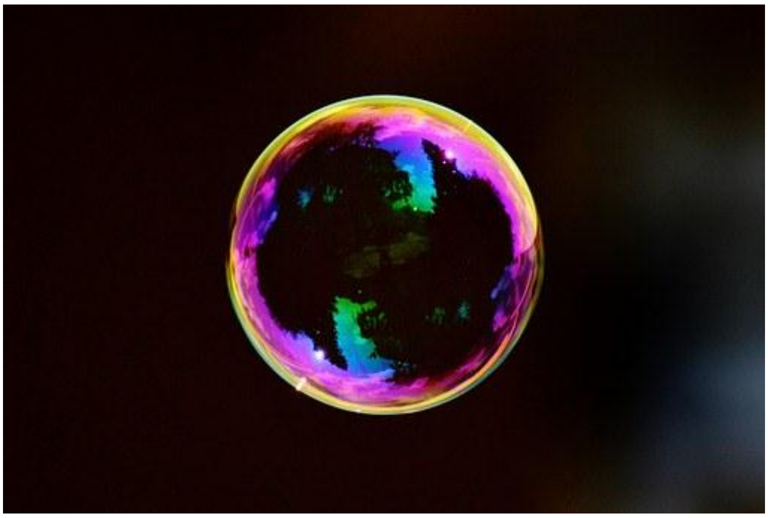
- **Molecular structure of gases:** **Gas** is one of the four fundamental states of matter (the others being solid, liquid, and plasma). A pure gas may be made up of individual atoms (e.g. a noble gas like neon), elemental molecules made from one type of atom (e.g. oxygen), or compound molecules made from a variety of atoms (e.g. carbon dioxide). A gas mixture would contain a variety of pure gases much like the air. What distinguishes a gas from liquids and solids is the vast separation of the individual gas particles. This separation usually makes a colourless gas invisible to the human observer.

4. INTRODUCTION

A solid sphere placed in the fluid under high pressure is compressed uniformly on all sides. We may have experienced this with an inflated balloon when taken inside a swimming pool.

Air bubbles have a perfect spherical shape.

We may have seen soap bubbles floating in air and they all have a perfect spherical shape



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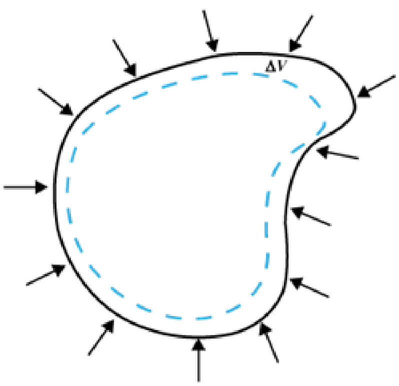

Picture shows the direction of pressure on a surface exposed to hydrostatic(pressure from all around) pressure

This may be explained

The pressure that is force per unit surface area is the same on all portions of the bubble. We may imagine ourselves in water and visualise the water pressure on all parts of our body. This is hydrostatic pressure. This is easy to feel if we submerge our hand in a bucket full of water the water pushes on our hand and arm, pressing it. Swimmer moves his arm against the pressure of water around his body.

https://content.active.com/Assets/Active.com+Content+Site+Digital+Assets/Triathlon/Galleries/Swimming+Burn/2.jpg

Deep sea divers wear special suits to counter the sea water pressure as they descend deeper in the sea or ocean. The excess pressure will cause temporary deformity in the body if the pressure is within elastic limit

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https://www.nasa.gov/sites/default/files/4873_0110_full.jpg

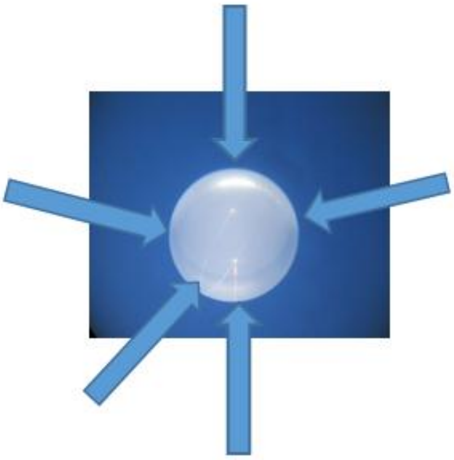
Picture shows hot air balloon in a sea of air

Do you think elasticity of material used for making the balloon is important?

5. VOLUMETRIC DEFORMING FORCE/ PRESSURE:

When a ball of volume V is taken to a depth h under water then the force applied by the fluid acts in perpendicular direction at each point of the surface and the body is said to be under hydraulic compression.

Picture shows equal pressure on the sphere from all directions



6. VOLUMETRIC STRAIN

The hydraulic pressure leads to decrease in its volume without any change of its geometrical shape.

The strain produced by a hydraulic pressure is called volume strain and is defined as the ratio of change in volume (ΔV) to the original volume (V).

Volumetric strain $= \frac{\text{change in volume}}{\text{original volume}}$

$= \frac{\Delta V}{V}$

Now imagine a rubber ball being compressed from all sides, Its easy to imagine that its volume will decrease, but, if on the other hand pressure on the rubber ball is decreased the volume would certainly increase.

So when pressure increases the volume decreases and when pressure decreases volume increases.

This is mathematically expressed using a negative sign.

Volumetric strain $= \frac{\text{change in volume}}{\text{original volume}} = -\frac{\Delta V}{V}$

Since the strain is a ratio of change in dimension to the original dimension,

It has no units or dimensional formula is $M^0 L^0 T^0$

7. VOLUMETRIC STRESS

The body develops internal restoring forces that are equal and opposite to the forces applied by the fluid (the body restores its original shape and size when taken out from the fluid).

The internal restoring force per unit area in this case is known as hydraulic stress and in magnitude is equal to the hydraulic pressure (applied force per unit area).

Volumetric stress = ΔP

8. MODULUS OF ELASTICITY

The **bulk elastic** properties of a material determine how much it will compress under a given amount of external pressure.

As considered earlier for young's modulus using Hooke's law

Volumetric stress is proportional to volumetric strain

$$\Delta P \text{ is proportional to } \frac{\Delta V}{V}$$

Or $\Delta P = B\frac{\Delta V}{V}$

The ratio of the change in pressure to the fractional volume change is called the **bulk modulus** of the material.

We have seen that when a body is submerged in a fluid, it undergoes a hydraulic stress (equal in magnitude to the hydraulic pressure). This leads to the decrease in the volume of the body thus producing a strain called volume strain.

The ratio of hydraulic stress to the corresponding hydraulic strain is called bulk modulus. It is denoted by symbol B.

$B = -\frac{\Delta P\, V}{\Delta V}$

Its unit is same as that for pressure Nm^{-2}

Dimensional formula is $[ML^{-1}T^{-2}]$

THINK ABOUT THESE

- **An air bubble rises from the base of a sea to the surface. Will the hydrostatic pressure change as it moves towards the surface?**

- **A hot air balloon is likely to change its volume as it climbs up . will its volume increase or decrease?**

- **Compute the bulk modulus of water from the following data:**

  Initial volume = 100.0 litre,

  Pressure increase = 100.0 atm (1 atm = 1.013 × 10^5 Pa),

  Final volume = 100.5 litre.

- **Compare the bulk modulus of water with that of air (at constant temperature). Explain in simple terms why the ratio is so large.**

- **What is the density of water at a depth where pressure is 80.0 atm, given that its density at the surface is 1.03 × 103 kg m^{-3}?**

- **Compute the fractional change in volume of a glass slab, when subjected to a hydraulic pressure of 10 atm.**

- **Determine the volume contraction of a solid copper cube, 10 cm on an edge, when subjected to a hydraulic pressure of 7.0×10^6 Pa.**

- **How much should the pressure on a litre of water be changed to compress it by 0.10%?**

- **Why is it that the water bubble of small size has larger pressure from inside then the water bubble of large size? When a bubble goes up in the atmosphere its volume increases. Can we say that it went through a volumetric strain? Can we calculate the bulk modulus of elasticity since neither the water not the air inside the bubble is solid?**

- **Among metals and non-metals which are more compressible?**

9. COMPRESSIBILITY

It is useful to describe compressibility as it tells us the elastic property of a bulk material under hydrostatic pressure. Hydrostatic stress is exhibited by all the three states of matter namely solids, liquids and gases. Solids are least compressible whereas gases are the most compressible.

The bulk modulus of solids are in the range of 10^{11} **N**$\mathbf{m}^{-2}$

And is about 50 times larger than that of water.

The incompressibility of the solids is primarily due to their rigid internal arrangement of atoms/molecules. The molecules in liquids and gases are less tightly coupled with their neighbours.

The reciprocal of the **bulk modulus** is called the **compressibility** of the substance.

The amount of compression for matter in solid and liquid state is much smaller than when matter is in gaseous state.

Here you must remember we are considering the same material in all three states for the above comparison.

Magnitude of bulk modulus

Bulk modulus for steel $= 160 \times 10^9 Nm^{-2}$

Bulk modulus for water $= 2.2 \times 10^9 Nm^{-2}$

A common statement is that water is an incompressible fluid. This is not strictly true, as indicated by its finite bulk modulus, but the amount of compression is very small. At the bottom of the Pacific Ocean at a depth of about 4000 meters, the pressure is about 4×10^7 N/m^2. Even under this enormous pressure, the fractional volume compression is only about 1.8% and that for steel would be only about 0.025 %.

Thus we see that the materials which have high value of Bulk modulus are less compressible.

The reciprocal of the bulk modulus is called compressibility and is denoted by k.

It is defined as the fractional change in volume per unit increase in pressure.

$k = (1/B) = -(1/\Delta p) \times (\Delta V/V)$

This can be seen from the data given in table that the bulk moduli for solids are much larger than for liquids, which are again much larger than the bulk modulus for gases (air).

Bulk moduli (B) of some common Materials

Material **Solids**	B (10^9 N m^{-2} or GPa)
Aluminium	72
Brass	61
Copper	140
Glass	37
Iron	100
Nickel	260
Steel	160
Liquids	
Water	2.2
Ethanol	0.9
Carbon disulphide	1.56
Glycerine	4.76
Mercury	25
Gases	
Air (at STP)	1.0×10^{-4}

Source:-NCERT

We can sum up

- Thus solids are least compressible whereas gases are most compressible.
- Gases are about a million times more compressible than solids!
- Gases have large compressibility, which vary with pressure and temperature.
- The incompressibility of the solids is primarily due to the tight coupling between the neighbouring atoms.
- The molecules in liquids are also bound with their neighbours but not as strong as in solids.
- Molecules in gases are very poorly coupled to their neighbours
- **Bulk modulus** describes the elastic properties of a solid or fluid when it is under pressure on all surfaces.
- The applied pressure reduces the volume of a material, which returns to its original volume when the pressure is removed, if the excess pressure is within elastic limit.

EXAMPLE

The average depth of Indian Ocean is about 3000 m. Calculate the fractional compression, ΔV/V, of water at the bottom of the ocean, given that the bulk modulus of water is 2.2×10^9 N m^{-2}. (Take g = 10 ms^{-2})

SOLUTION

The pressure exerted by a 3000 m column of water on the bottom layer

$p = h\rho\, g = 3000 \text{ m} \times 1000 \text{ kg m}^{-3} \times 10 \text{ m s}^{-2} = 3 \times 10^7 \text{ kg m}^{-1} \text{ s}^{-2} = 3 \times 10^7 \text{ N m}^{-2}$

Fractional compression

ΔV/V,

is $\Delta V/V = \text{stress}/B = (3 \times 10^7 \text{ N m}^{-2})/(2.2 \times 10^9 \text{ N m}^{-2}) = 1.36 \times 10^{-2}$ or 1.36 %

EXAMPLE

A solid rubber ball has its volume reduced by 14.5% when subjected to a uniform stress of $1.45 \times 10^4 Nm^2$. Find the bulk modulus of rubber.

SOLUTION

Volume strain = 14.5% = 14.5×10^{-2}, Volumetric stress = 1.45×10^4,

To Find Bulk modulus of elasticity

$$\text{Bulk modulus of elasticity} = K = \frac{Volumetric\ stress}{Volumetric\ strain}$$

∴ $K = (1.45\times10^{4}) / (1.45\times10^{-2}) = 10^{5} N/m^{2}$

Bulk modulus of elasticity of rubber is 10^{5} N/m^{2}

EXAMPLE

A volume of 5 litre of water is compressed by a pressure of 20 atmospheres, if the bulk modulus of water is 20×10^{8} N/m^{2}. Find the change produced in the volume of water. Density of Mercury = 13,600 kg/m^{2};

g = 9.8 m/s^{2}. Normal atmospheric pressure = 75 cm of mercury.

SOLUTION:

Original Volume =5 L =5×10^{-3} m^{3},

Pressure =dP = 20atm =$20\times75\times10^{-2}\times13600\times9.8$ N/m^{2},

Bulk modulus of elasticity of water =20×10^{8} N/m^{2}.

So to calculate the Change in volume =dV

Volumetric stress = dP

Bulk modulus of elasticity = $K = -(dP\times V)/dV$

∴Change in volume =$dV = (dP\times V)/K$

∴ $dV = 5\times10^{-6}\ m^{3} = 5 cm^{3}$

The change produced in the volume is $5cm^{3}$.

EXAMPLE

A solid brass sphere of volume 0.305 m^{2} is dropped in an ocean, where water pressure is 2×10^{7} N/m^{2}. What is the change in volume of the sphere?

SOLUTION:

Original Volume = $0.305m^{3}$,

Pressure = dP = 2×10^{7} N/m^{2},

Bulk modulus of elasticity = K= 6.1×10^{10} N/m^{2}.

To calculate the change in volume of the sphere

Volumetric Stress =dP

Bulk modulus of elasticity = $K = (dP\times V)/dV$

Change in volume = $dV = (dP\times V)/K$

Change in volume = $dV = (2\times10^{7}\times0.305)/ (6.1\times10^{10})$

$dV = 10^{-4}\ m^3$

Change in volume = $10^{-4}\ m^3$

9. BULK MODULUS AROUND US

Sound waves

You will recall sound waves are mechanical waves. They need a medium for propagation. They travel in any medium.

The bulk modulus of a solid influences the speed of sound and other mechanical waves in the material. It is for this reason why sound travels faster in solids and slowest in gases.

Earth quakes and seismic activity

Bulk modulus plays a role in the energy stored in solid material in the Earth's crust. This build-up of elastic energy can be released violently in an earthquake, so knowing bulk moduli for the Earth's crust materials is an important part of the study of earthquakes. The bulk modulus is one of the factor in the speed of seismic waves from earthquakes.

Deep Sea Divers

The **water pressure** is very high. The pressure from the water would push in on the person's body, causing any space that's filled with air to collapse. (The air would be compressed.) So, the lungs would collapse.

Atmospheric Diving Suit (ADS) is a suit of armour, with elaborate pressure joints to allow movement of joints while maintaining an internal pressure of one atmosphere.

The ADS can be used for very deep dives of up to (700 m) for many hours, and eliminates the majority of physiological dangers associated with deep diving; the occupant need not decompress, there is no need for special gas mixtures, and there is no danger of decompression sickness. Divers do not even need to be skilled swimmers.

Although various atmospheric suits had been developed, none of these suits had been able to overcome the basic design problem of constructing a joint which would remain flexible and watertight at depth without collapsing up under pressure.

Aquatic life

Evidence relating to hydrostatic pressures impact on metabolism has been recorded, for example an experiment designed to test the effects of hydrostatic pressure on this experiment was conducted by replicating hydrostatic pressure and on cell retrieved from a terrestrial animal. It is very hard to capture deep sea fish and bring them back to the laboratory and to simulate deep sea conditions for experiments.

photo Eel Blue Deep Sea

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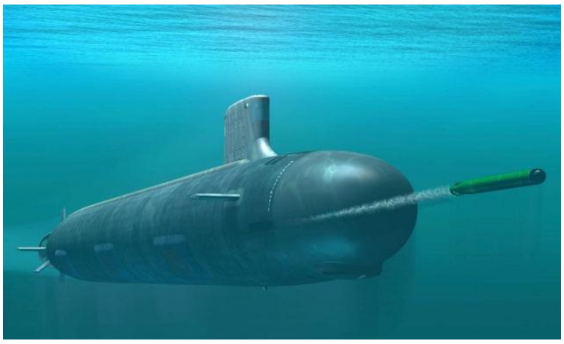
This suggests that hydrostatic pressure affects an organism's metabolism that causes large organism size. However, the deep sea fish, *Melan stigma pammelas,* is one of the very few organisms which can survive being brought to the laboratory Making this species perfect for analysing the effects of certain environmental impacts such as temperature and hydrostatic pressure. According to Belman & Gordon, (1979), who undertook experiments on the deep sea mesopelagic fish; analysing the effects of temperature and hydrostatic pressure effect on metabolism e.g. the oxygen uptake and using these results to compare to shallow water fish species. The results concluded from all experiments that temperature and hydrostatic pressure on metabolism with a range of 17 to 170 atmospheres.

It is widely regarded that as depth increases, pressure will also increase. At greater depths the pressure increases due to the sheer volume of water above. Every 10 metres pressure will increase by 14.5psi (psi stands for pounds per square inch). Taking that into consideration, the deep sea is classified to be 200m and deeper, this means at great depths pressure is very high. How does this impact and affect a deep sea organism? Pressure at the surface and terrestrial environment has only a pressure of 1 atmosphere or even less, however the ocean that has an average depth of 3800 metres means this equates to 380 atmospheres Trenches can be found which exceed depths of 6000 metres Even at these extreme depths organisms are found not just surviving but thriving.

Submarines

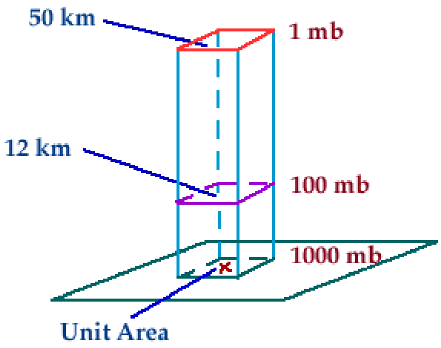


The next thing to think about is how do submarines go up and down. Well, submarines have what they call " ballast tanks " . These tanks fill up with water to sink the submarine. When the submarine wants to go to the surface the tanks are filled with air and the submarine goes up. As the submarine goes deeper and deeper, assuming it stays perfectly oriented so that no air can escape, the air will be compressed by water pressure. The volume of the air will shrink, making the water level higher inside its tank.

Depending on how deep you go, the pressurized air could kill a person.

Inside the aeroplane the cabin is pressurised.

The atmospheric pressure reduces by for every one kilometre as we go higher. The commercial aircraft flies at about 11-13 km above the earth surface. To make the cabin comfortable, it is pressurised - such that the humans do not suffer haemorrhage due to blood pressure being greater than the atmospheric pressure at that altitude.



mb is millibar = 76cm of mercury =1 atmosperic pressure.

11. SUMMARY

- **Volumetric strain:** is the unit change in **volume**, i.e. the change in **volume** divided by the original **volume**.
- **Volumetric stress:** which cause the change in volume
- **Hydraulic stress:** is the measure of the internal force per unit area acting on the liquids.
- **Bulk modulus K:** of a substance is a measure of how incompressible/resistant to compressibility that substance is. It is defined as the ratio of the infinitesimal pressure increase to the resulting relative decrease of the volume.
- **Fish, aquatic life on seabed, deep sea diver suits and submarines account for hydrostatic pressure and bulk modulus of materials**