BASIC THEORY THE THEORY OF LIFTING BAGS

Safe and effective utilization of lifting bags underwater requires both the operator and the diver to have a basic understanding of certain physical laws, and the ability to make calculations relevant to pressure, volume, buoyancy etc. Without prior consideration to the weight of the object to be lifted, or the volume and number of lifting bags to be utilized, there can be no guarantee of success.

Although most divers will have a certain basic appreciation of the Laws of Physics relevant to diving, i.e. Archimedes principle relating to buoyancy; absolute pressure; hydrostatic pressure and Boyles law, they may not have experience of relating these to practice, therefore a brief summary will not be out of pace.

ARCHIMEDES' PRINCIPLE

This explains the nature of buoyancy and why certain objects become heavier on being removed from underwater. The principle states that any object, whether wholly or partially submersed in a liquid experiences an upward thrust equal to the weight of the liquid displaced. The buoyancy of an immersed object can therefore be calculated by subtracting the weight of the object from the weight of the displaced liquid. If the weight of the object is less than the weight of the displaced liquid, then the object is said to have positive buoyancy, and it will float. Should the two weights turn out to be exactly equal, then the object is said to have neutral buoyancy, which means that to have negative buoyancy, or to sink, the weight of the object must be greater than the liquid it displaces.

The buoyant force of a liquid is dependent on its density, which is its mass per unit volume. Fresh water, with a density or mass of 62.3*54* lbs per cubic ft (1000 kg/m^3), offers less upward thrust than salt water, which has a density of 63.936 lbs per cubic ft (1024 kg/m^3). Hence somewhat less buoyancy is required to lift an object in the sea than the same object would require if it was submerged in a river or lake.

If this is applied to a practical problem, then consider a solid block of steel, measuring 12 x 12 x 12 inches, i.e. 1 cubic foot. From a table of weights, it can be established that 1 cubic foot of steel weighs *485* lbs in air. Should this block now be completely submerged in salt water it would displace 1 cubic foot of water, which we already know weighs 63.936 lbs (or 64 lbs to the nearest decimal point) (29 kg) per cubic foot. Hence with an upward force of 64 lbs the weight of the steel is now only 421 lbs (191 kg) (*485* lbs - 64 lbs). In a fresh water situation the same block would have a negative buoyancy of 422.6 lbs (191.7 kg), and hence is slightly heavier. Although a very simple example this serves to illustrate the need, in the best interests of safety and efficient salvage operations, to be aware of what is required to be lifted, and hence the capacity of the lifting bag necessary.

HYDROSTATIC PRESSURE

Hydrostatic pressure results from the weight of water acting on a submerged object: as with atmosphere above the surface, it is equal in all directions at a specific height or depth. This underwater pressure increases at the uniform rate of 14.7 lbs per square inch (1.013 bar) for every 33 ft (10 m) of depth, which equals 0.445 lbs per sq. in. for every foot of descent in salt water and 0.432 lbs per sq. in. in fresh water (0. 098 bar/m in fresh water or 0.1005 bar/m in salt water). When using lifting bags it is important to remember that whilst air is being fed inside them, there will be pressure differential due to the bags physical dimensions, and that each bag has its own designed working pressure, no matter at what depth it is being used.

ABSOLUTE PRESSURE

Absolute pressure exerted on a submerged body is the sum of the atmospheric pressure and the hydrostatic pressure. Normal atmospheric pressure at sea level is accepted as being 14.7 psi

(1.013 bar), therefore the absolute pressure at a depth of 60 ft (18.3 m) of seawater is as follows:

a) Hydrostatic pressure is 60 x 0.445 psi = 26.7 psi (1.84 bar)

b) Atmospheric pressure at sea level = 14.7 psi (1.013 bar)

c) Therefore absolute pressure is 26.7 + 14.7 = 41.4 psi (2.853 bar)

Absolute pressure may be expressed as ‘atmospheres absolute’, i.e. at (c) or as pressure in ‘pounds per square inch absolute’ or psi (c).

Having considered the various pressure effects on a lifting bag depth, it is now necessary to look at the result of bringing that bag to the surface, still inflated. All divers are aware of the dangers of holding ones breath during ascent, which can result in a ruptured lung as the expanding air seeks a form of escape; the same basic physics applies to a lifting bag on ascent, and for the same reasons the diver must ascend at a controlled rate, exhaling or venting as he goes up, so the lifting bag must be vented, otherwise it will burst.

BOYLES’ LAW

Boyles’ Law states that at a constant temperature, the volume of any gas will vary inversely with the absolute pressure, whilst the density will vary directly with the pressure. In simpler terms, the pressure increases, the volume will decrease, and as the pressure decreases (as when returning to the surface), so the volume of gas will expand. Whilst the density and temperature are important considerations in scientific work, for practical salvage purposes, they can be ignored, and we need only be concerned with the matter of contraction and expansion as the depth alters.

If we consider how Boyles’ Law relates to a 1 tonne lifting bag, with a capacity of 35 cubic feet(1 m^3) of air, first at the surface and submerged, the basic formula for a practical use is:

$$V_1 = (P_1 \times V_2) / P_2$$

where: V_1 = The air capacity of the bag at 1 atmosphere absolute (14.7 psi).

V_2 = Resultant volume in cubic feet.

P_1 = Starting pressure in psi (a).

P_2 = New pressure in psi (a).

What will happen to the volume of the bag if it is now taken from the surface to a depth of 60 ft (18.3 rn) in sea water?

Firstly, calculate the absolute pressure relevant to the maximum depth, i.e:

60 x 0.445 + 14.7 = 41.4 psi (a) or 18.3 x 0.1005 + 1.013 = 2.85 bar

Resultant volume at depth $= \frac{14.7 \times 35}{41.4}$ or $= \frac{1.013 \times 1}{2.85}$

= 12.42 cubic feet = 0.355 m^3

If the lifting bag were completely full of air at the same depth of 60 ft of seawater, what volume would have been vented off as a result of the decreasing pressure on returning to the surface?

Resultant volume at surface $= \frac{41.4 \times 35}{14.7}$ or $= \frac{2.85 \times 1}{1.013}$

$= 105$ cubic feet $= 2.81 m^3$

Hence the volume vented off is the resultant volume at the surface, minus the bag capacity, i.e.:

Volume to be vented = 105 - 35 or = 2.81 -1

= 70 cubic feet = $1.81\ m^3$

A useful 'rule-of-thumb' is to remember that the 35 cubic feet of air is required to lift 1 ton (long) or 2240 lbs. i.e.: $\frac{2240}{64}$ lbs $= 35\ ft^3$

PRACTICAL CONSIDERATIONS

With some appreciation of the basic physics and calculations involved, let us now consider a theoretical problem in more detail: Assume that there is a piece of wreckage at the depth of 75 ft in the sea, which is to be raised. The basic information required is necessary in order to answer the following four questions:

a) What is the net 'in water' weight of the wreckage?
b) What is its displacement?
c) What number and volume of lifting bags are necessary?
d) What minimum volume of air will be necessary?

Assume that the estimated mass of the wreckage is 9 tons (long), and that the material is steel. Now convert the estimated mass into lbs:

9 x 2240 = 20160lbs

Also determine, from the given table of Densities of Material, the density of steel measured in lbs/ft^3:

Density of steel = $485\ lbs/ft^3$

a) $\frac{\text{Gross weight in lbs in air}}{\text{Density of Material}} = \text{Displacement in } ft^3$

$\frac{20160}{485} = 41.56\ ft^3$

Displacement in ft^3 x wt of 1 ft^3 seawater = Buoyancy force (in lbs)

$41.56\ ft^3 \times 64\ lbs/ft^3 = 2,660$ lbs

Therefore the 'in water' weight = 20160 -2660

= 17500 lbs

NB: This 'in water' weight is only estimated, since it is difficult to obtain an accurate measurement of weight of irregular objects underwater.

b) $\frac{\text{In water weight of item in lbs}}{\text{Wt of 1 ft}^3 \text{ seawater in lbs}}$ = total displacement to achieve neutral buoyancy. = 273.43 ft^3

c) Lift in tons = $\frac{\text{displacement}(ft^3)}{\text{vol to lift 1 ton in } ft^3}$ = $\frac{273.43}{35}$

Therefore to render the lift neutrally buoyant only, it would be necessary to apply 7.812 tons. To achieve positive buoyancy, 8 tons of lift would be a reasonable calculation, depending on the geometry of the lift. Of the 8 tons of lift at least 1 ton would be used as buoyancy control (see comments later).

Note that 7.812 tons represents *97.65%* of the 8 tons of lift available, therefore *2.35%* or 421 lbs would represent the positive buoyancy.

i.e. 8.00 tons - 7.812 tons = 0.188 x 2240 lbs

=421 lbs

421 lbs divided by 64 lbs lifting capacity of 6.58 ft^3

d) (i) Absolute pressure in atmospheres and psi:

75 ft depth x 0.445 lbs/ft change + 14.7 = 48 psi (a)

$\frac{\text{48 psi (a)}}{\text{14.7 psi}}$

= 3.265 Atm (a)

(ii) Total volume of air required to inflate lifting bags representing 8 tons at 75 ft depth

8 tons x 35 ft^3 x 3.265 Atm(a) = 914ft^3

Since a compressor would be required to supply this volume of air, assume a supply capacity of 75 ft^3 per minute, then it will take approximately 12 minutes to inflate, but allowing a 1/3 increase for flow loss in the hose, then the time taken to inflate will be:

914 ÷ 75 ft^3 min = 12.18 minutes

12.18 x 0.33 = 4.05 minutes

Total time = 12.18 + 4.05 = 16.23 or 17 minutes.

AIR REQUIREMENTS FOR LIFTING BAGS

Using the 'rule of thumb', already mentioned, that it takes 35ft^3 of air to lift 1 ton, it follows that a 3 ton lifting bag would require:

$$35 \times 3 = 105ft^3 \text{ air [at 1 Atm (a)]}$$

However, with a pressure relief valve fitted, which ensures that the internal pressure is maintained at 2 psi above ambient, then more than 105 ft^3 will be required. Since 2 psi is 13.6 % of 1 atmosphere: (2 ÷ 14.7 psi) x 100 = 13.6% Thus, for a 3 ton bag with a relief valve, the revised volume of air necessary is: 105 x 1.136 = 9.28 ft^3

Considering a more practical problem; what calculations are necessary to use the 3 ton totally enclosed air bag at a depth of 50 ft in seawater with a compressor of 50 ft^3 per mm available?

a) Absolute pressure depth: 50 + 33 ft = 83 ft.

b) Atmospheres absolute: 83 ÷ 33 = *2.5* atm

c) Air required for 3 ton bag: 35 x 3 = 105 ft^3.

d) 2 psi over-pressure = 0.136 atm.

e) Total air required to operate relief valves at one atmosphere absolute: 105 + 1.136 = 119.28 ft^3.

f) **<u>Total air required at 50 ft</u>:** 105 x 2.636 = 234.8 ft^3.

g) Compressor time to fill bag: 234.8 ÷ 50 cfm = 4.70 mins.

h) Air flow loss in hose: 4.70 x 0.333 = 1.565 mins.

i) **<u>Total time to fill bag</u>:** 4.70 + 1.57 = 6.27 mins.

A major advantage of the totally enclosed lift bag is the ease with which surface towing can be achieved with the bags still fitted, this may eliminate the use of a crane barge for example, and hence greatly reduce the cost of a contract.

EXAMPLE

Whilst the previous example was calculated in imperial units, it may be necessary to be familiar with the same sort of calculations based on metric units. The following two examples show the working for both imperial and metric units.

What is the weight of a block of concrete measuring 46 x 30 x 23 cm (18 x 12 x 9 in) in air? What will its weight be when it is submerged in saltwater?

IN AIR

In Metric Units

$W = pV$

$p = 2323\ kg/m^3$ (see density table)

$V = 46 \times 30 \times 23\ cm^3$

Convert to metres³

$= \frac{46 \times 30 \times 23}{10^6}$

$= 0.03174\ m^3$

$W = 2323\ kg/m^3 \times 0.03174 m^3$

73.73 kg

In Imperial Units

$W = pV$

$p = 145\ lb/ft^3$

$V = 18 \times 12 \times 9\ in^3$

Convert to feet³

$= \frac{18 \times 12 \times 9}{1728}$

$= 1.125\ ft^3$

$W = 145\ lb/ft^3 \times 1.125\ ft^3 =$

= 163.125 lbs

UNDERWATER

Metric

$W_{sub} = V (p_o - p_w)$

$V = 0.3174\ m^3$

$p_o = 2323\ kg/m^3$ (from table)

$p_w = 1026\ kg/m^3$ (from table)

$= 0.01374 \times (2403 - 1026)$

= 41.2 kg

Imperial

$W_{sub} = V (p_o - p_w)$

$V = 1.125\ ft^3$

$p_o = 145\ lbs/ft^3$ (from table)

$p_w = 64.041\ lbs/ft^3$ (from table)

$= 1.125 \times (150 - 64)$

= 91.125 lbs

Having looked quite closely at the theoretical aspects of this subject, let us now consider the practical application, and the first consideration must be 'how much positive buoyancy is required in a lift?'

One of the major problems associated with the buoyant recovery system is controlling the ascent velocity once the actual lift has commenced. This is particularly true of collapsible lifting bags for a number of reasons. If the load is less than the bag capacity, ascent will commence before the bag has reached its maximum displacement. As it ascends, the gas will expand within the airbag, hence increasing its net buoyancy, which in turn will increase the ascent rate. Therefore it is important to use a bag fitted with a pressure relief valve. It is most important to select bags with a lifting capacity equal to the load, with possibly a smaller bag or crane assistance to provide the positive buoyancy control required. In any event, the ascent rate should never exceed 2 -3 feet per second.

What might be the result of too fast an ascent rate?

Should a lifting bag rise at a rate faster than 10 feet per second, a phenomena known as a ‘velocity-head’ may develop on the top surface, in which the force due to the upward motion reacts against the top face, forming a pressure head, deforming the bag and causing it to become unstable. In an extreme situation this may cause the bag to dump air, lose buoyancy and thus let the load return to the bottom. The ascent rate is therefore vital to the successful outcome of any lifting project. Accurate estimation of acceleration and final ascent speed is more difficult than the previous calculations. Initial acceleration is given by the total lift force divided by the total payload mass. In this case, in addition to the payload itself, the mass includes an unknown quantity of entrained or trapped water. The final ascent speed is determined by the total lift force; which is in turn determined by the shape and drag area of the lift bag and payload combination.

The form of the equation is:

Lift Force = Mass x Acceleration + Pressure Drag + Friction Drag

$$\text{Lift Force} = M \times Acc + 0.5 \times p \times V^2 \times [Cp \times Al + Cf \times A2]$$

Where: M = Total mass (including added mass of water)

- Acc = Acceleration
- p = Water density
- Cp = Pressure or Form Drag coefficient - an empirical constant
- A1 = Horizontal area presented by payload and lift bags
- Cf = Friction Drag coefficient -a part empirical constant which also includes viscosity
- A2 = Surface area in contact with flow

Accurate selection of bag capacity for precise acceleration and speed control is difficult because of the uncertainty in estimates of M, Cp and Cf; and also possibly A1 and A2.

A ‘rule of thumb’, which has been found to give satisfactory results, and avoid excessive ascent speeds is to provide a lift force which is not more than 20% greater than the payload in-water weight.