2

The Physics and Physiology of Deep Diving

Water Pressure or Hydrostatic Pressure. A cubic foot of salt water weighs 64 lbs., so that if a box measuring one foot in each direction (length, breadth and depth) were slung from a hook and filled from the sea there would be an extra weight of 64 lbs. on the hook, and the bottom of the box would have the same weight pressing on it. Now the bottom of such a box would have an area of 144 square inches, and, being level, would have the weight of the water evenly distributed all over it—in other words, each of the 144 square inches would support its own share of the 64 lbs., and that share would be $\frac{64}{144}$ or 0·44 lb.

Suppose now, that keeping the same bottom, the sides of the box were built up to two feet high. It would now hold two cubic feet of water, so that when full the bottom

TABLE I. Illustrating water pressures at important depths

(A more complete table of water pressures for all depths up to 1,020 feet is given in Chapter 16).‡

Depth of actual dives—sea water	Remarks	Positive pressure	Absolute pressure
0 feet	On surface	0 lbs. per sq. in.	1·0 atmosphere = 14·7 lbs. per sq. in.
2¼ ,,		1 ,, ,,	15·7 lbs. per sq. in.
33 ,,		14·7 ,, ,,	2·0 atmospheres
132 ,,	*Laurentic* salvage	58·8 ,, ,,	5·0 ,,
240 ,,	U.S. Navy divers using oxy-helium breathing mixture with flexible dress in salvage of U.S. Submarine *Squalus*, 1939	107 ,, ,,	8·28 ,,
300 ,,	Practical limit in Siebe, Gorman & Co.'s flexible dress diving with normal air supply*	133.3 ,, ,,	10·0 ,,
344 ,,	Hilton diving in Siebe, Gorman & Co.'s flexible dress, with normal air supply 1932*	152·8 ,, ,,	11·4 ,,
400 ,,	*Egypt* salvage, 1932; in observation chamber	177 ,, ,,	13 ,,
438 ,,	*Niagara* salvage, 1941; in observation chamber	194·7 ,, ,,	14·24 ,,
440 ,,	United States Navy divers in U.S. Navy flexible dress, using oxy-helium breathing mixture, 1938†	195·6 ,, ,,	14·27 ,,
540 ,,	P. O. Bollard, R.N. Record dive in Siebe, Gorman & Co.'s flexible dress using oxy-helium breathing mixture, 1948*	240·2 ,, ,,	17·36 ,,
3,028 ,,	Dr. W. Beebe in "Bathysphere" observation chamber, 1934 ..	1,343·8 ,, ,,	92·76 ,,
35,640 ,,	Greatest known ocean depth ..	15,840 ,, ,, = 7·07 tons	1080·0 ,,

* Injector type dress with CO_2 absorbent.

† A simulated depth of 500 feet = 222·6 lbs. per square inch = 15·5 atmospheres was attained some years ago by divers of the United States Navy using helium-oxygen mixtures as their air supply.

‡ For latest Ocean descents see Appendix F

would have to support a weight of 128 lbs. or 0·88 lb. per square inch. If it were built up to three feet high, so as to hold thrice as much as in the first case, then the weight on the bottom would be 1·3 lbs. per square inch.

Carrying on this idea, it can be seen that the bottom will have to support an extra 0·44 lb. per square inch for every foot depth of water that is piled above it, so that, if a box, say, one foot square and 120 feet deep were filled with water, then the bottom would have a pressure bearing upon it of $120 \times 0{\cdot}44$ lb. or 53·4 lbs. per square inch. Calculation will show that, though we have been working with an imaginary box one foot square, it is the depth alone that matters, and not the length and breadth; no matter whether the box is a few inches square or as wide as the Atlantic Ocean, the pressure on its bottom will be 0·44 lb. per square inch for every foot depth of salt water above it.

Up to now, we have only spoken of downward pressure on the bottom, and if water were a solid, like ice, that is the only sort of pressure it would exert; but water is a fluid capable of pushing sideways as well as downwards; it exerts its pressure in all directions at once, and a gauge fixed in the side of the box, level with the bottom, would register the same pressure per square inch as that pressing downward on the bottom, while a gauge fixed in the side one foot below the surface would show a pressure of 0·44 lb. per square inch, and so on. Water presses inwards as well as outwards, so that any object sunk in water, like a submarine or a diver, must also sustain a pressure of 0·44 lb. per square inch for every foot of depth to which it is sunk.

A cubic foot of fresh water weighs 62·5 lbs., hence fresh water is about 3 per cent lighter than sea water, and the pressure at a given depth in wells or fresh water lakes is about 3 per cent less than it would be at the same depth in the sea. The last column of the above table, "absolute pressure", must now be explained.

Pressure of air. Air has weight; for example, an ordinary 100 cubic feet cylinder of compressed air at 60° Fah. weighs 7·6 lbs. more when it is charged to a pressure of 120 atmospheres than when it has been emptied. On the surface of the earth we are living, as it were, at the bottom of an ocean of air some miles deep, and its weight presses on our bodies in the same way as water presses on anything sunk in it. This air pressure is so universal that it is taken for granted, and ordinary pressure gauges do not show it; they register only pressures in excess of that which the air is constantly exerting. There are special pressure gauges, familiar to us as aneroids or barometers, which do register the air pressure in which we live; they show that it varies a little from day to day, being generally higher in fine than in stormy weather, but that, taking an average, the pressure on the surface of the earth is about 14·7 lbs. per square inch. This is called atmospheric pressure, or a pressure of one atmosphere. Just as in water, so in air; the greater the depth, the greater is the pressure; thus at the bottom of a coal mine an aneroid shows a greater pressure than at the surface (e.g. a mine 2,200 feet deep, would have a pressure of 16 lbs. per square inch); at the summit of Mount Everest, which is 29,140 feet high, the pressure is no more than 4·6 lbs. per square inch, and at 10½ miles, the height reached by Prof. Piccard in his pioneer balloon ascent to the stratosphere, there was so little air remaining above him that the pressure was only 1·3 lbs. per square inch. Air, being a gas, differs from water in that its density is proportional to the pressure and therefore, at such heights, not only is the pressure low but the absolute amount of oxygen present in a unit volume becomes less and less.

As the average air pressure at the surface of the earth of 14·7 lbs. per square inch is called a pressure of one atmosphere, a pressure of 29·4 lbs. per square inch would be called a pressure of two atmospheres, and so on.

Thus, there are two different ways of reckoning pressure. The first disregards the standing pressure of the air, and only measures pressures over and above it; these are called positive pressures. The second method includes the atmospheric pressure in the totals, and calls them absolute pressures. A glance at the third and fourth columns of Table I will make this clear. Unless the contrary is stated, the word "pressure" in books or conversation is always taken as meaning positive pressure, and ordinary pressure gauges, such as those on boilers, hydraulic machinery or divers' air pumps, record positive pressures only. It may, therefore, be wondered why there should be any need to bother about absolute pressures. As will be seen later, the reason is that when such problems as the amount of air required by a diver at different depths, or the rate at which a sunken submarine will flood, have to be worked out, the necessary calculations have to be made in terms of absolute pressure.

Forcing Air Down to a Diver. The old-time inventors, whose curious designs are described in the "History of Diving and Diving Appliances"* in a later chapter, often arranged to supply their divers from leathern bellows, supposing, no doubt, that the apparatus which they knew from experience to be capable of supplying plenty of air to a forge or an organ would easily furnish the lesser quantity needed by a man. They had not reckoned with the water pressure, the effect of which can be demonstrated by a simple experiment.

Take a pipe or tube three to five feet long, plunge it into water, and then blow in at the top so that bubbles escape from the lower end; it will be found that, as the pipe is plunged more deeply into the water, the effort required to force down the air increases, and at five feet is beyond the power of most people's lungs. The reason is simply that before a bubble can escape, it has to push away the water from the end of the tube, and it can only do this by pushing with at least as high a pressure as the water is exerting at the same place. Thus, to blow bubbles out of the end of a tube whose end is sunk two and a quarter feet under water would require an air pressure of 1 lb. per square inch (see Table I), and if a sensitive pressure gauge were attached to the side of the tube, as shown in Fig. 16, it would show that this pressure is, in fact, exerted. Do not persist with this experiment too long, as the developing of such pressures in the chest interferes with the return of blood to the heart and its output of blood falls, causing the subject to feel faint. To force air down to a diver (in an unarmoured diving dress) at a depth of 112 feet would need an air pressure of 50 lbs. per square inch. As bellows are, of course, incapable of exerting any such pressure, properly designed air pumps or compressors are required. It should now be easy to understand how and why the pressure gauge on a diving pump indicates the depth of the diver.

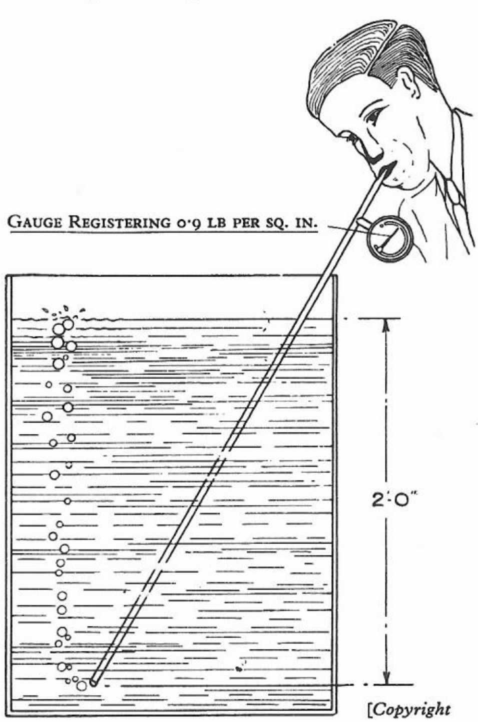

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Fig. 16. Illustrating the pressure required to breathe against 2 feet of water

Compression of Air and Change of Volume. For the sake of simplicity, let us imagine the case of a diving bell, or any vessel closed at the top and open at the bottom, being lowered into water, no means of supplying air being supposed to exist (see Fig. 18). If it is lowered to a depth of 33 feet in the sea, the water pressure all round it will be 14·7 lbs. per square inch, and this pressure can get into the bell through the

* Part II, Chapter 4.

open bottom and act on the air which it contained when it left the surface. Now, air is compressible and can be squeezed into a smaller space than it originally occupied, so that, in the present case, the water will squeeze the air up towards the top of the bell. It happens that a squeeze of 14·7 lbs. per square inch compresses air to exactly half its original volume, so that, if the bell entered the water quite full of air, by the time it reached a depth of 33 feet the water would have risen halfway up inside it, and the air would occupy the upper half only. This air being pressed on by the water would acquire the same pressure, namely, 14·7 lbs., and, naturally, if a man were sitting in the bell, half immersed, his legs would be in water at this pressure, his head in air at the same pressure, and his lungs full of air also at 14·7 lbs. per square inch. The walls of the diving bell are subjected to very little strain, as the air pressure inside practically balances the water pressure outside.

If the bell is lowered to 66 feet (29·4 lbs. pressure), the contained air will be squeezed into a still smaller volume, and the water will rise two-thirds of the way up to the top; and at 99 feet depth the bell will be three-quarters filled with water and only one-quarter filled with air. Note that the bell always contains the same quantity or weight of air, but this quantity occupies a smaller and smaller space as the pressure on it increases—in other words, its density increases.* To find out how high the water would rise at different depths, or rather the volume which a certain quantity of air would occupy at different pressures, we must divide the volume which it occupied at the surface (or at a pressure of one atmosphere absolute) by the new absolute pressure in atmospheres.

TABLE II

The volume to which 120 cubic feet of free air would be reduced at different pressures

Depth	Positive pressure	Absolute pressure	Volume
Surface	0 lbs. per sq. in.	1 atmosphere	120 cu. ft.
33 ,,	14·7 ,, ,, ,,	2 ,,	60 ,,
66 ,,	29·4 ,, ,, ,,	3 ,,	40 ,,
99 ,,	44·1 ,, ,, ,,	4 ,,	30 ,,
132 ,,	58·8 ,, ,, ,,	5 ,,	24 ,,

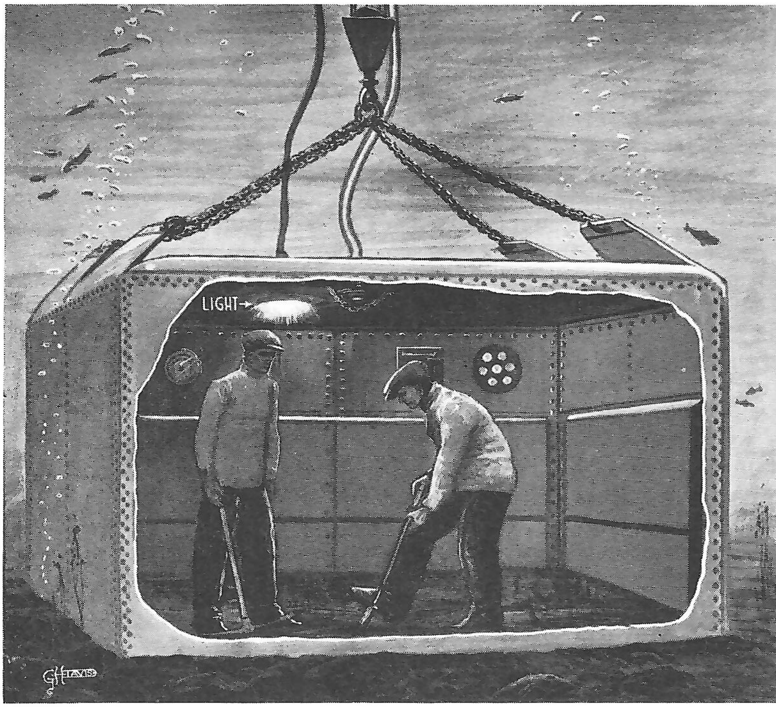
This is illustrated graphically in Fig. 18. It shows the extent to which the air in a Siebe, Gorman diving bell would be compressed as it was lowered to greater depths. The important feature which must be noted, because it affects all diving work, is that there is a great change of volume in the first part of the descent (near the surface), but that, as the descent continues, the steadily increasing pressure has less and less effect in further reducing the air volume. Or, to put it another way, changes of depth have much more effect on the air volume in shallow water than in deep.

Now, in order to prevent entry of water into the diving bell, an air pipe is connected to an inlet valve fitted in the roof, and air, at a pressure equivalent to the depth to which the bell is lowered, is pumped down from the surface to supplement the air originally contained in the bell.

We have seen that if the bell is lowered to a depth of, say, 66 feet, the air pump will have to exert a pressure of about 30 lbs. per square inch in order to keep the water out. In actual practice, of course, the air supply, in adequate quantity and at the necessary pressure, follows up the bell as fast as the latter descends, so that the water is kept below the footboard all the time. The surplus air escapes under the edge of the bell, and so affords ventilation for the men working inside.

Object of Non-return Valves. The air pipe supplying a diving bell must be strong enough to resist the air pressure. At the lower end, where the pipe joins the bell, this pressure is nearly balanced by the water pressure outside the pipe, but at the

* These facts constitute what is called "Boyle's Law", which is that the volume of a gas varies inversely as the pressure, whilst the density varies directly as the pressure.



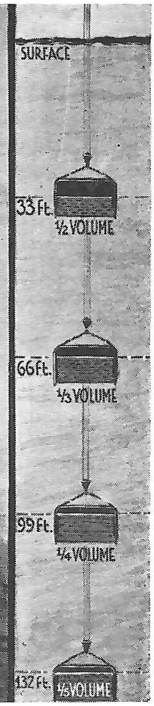


Fig. 17 Fig. 18

Fig. 17. Diving bell in use, the compressed air excluding the water

Fig. 18. Diagram showing to what volume atmospheric air would be compressed by the water at various depths if an adequate supply of air were not delivered to it

upper end there is no such support, and, consequently, that is where a weak pipe would be most likely to burst. In such an event, if there were no safety arrangement, all the compressed air in the diving bell would escape, the water level in the bell would rise till it was completely flooded and the men would be drowned. To prevent the possibility of such an accident, a spring-loaded non-return valve is always fitted at the junction of the pipe with the diving bell. This valve (shown diagramatically in Fig. 17) allows air to flow freely into the bell, but in the case of a burst air pipe it would close and prevent any escape in the reverse direction. We shall see later (pages 61 and 65) that divers' helmets are fitted with non-return inlet valves for a similar reason.

Effect of Pressure on Men. If one puts the tip of the thumb (area about one square inch) on the edge of a table and gently lowers a 1 cwt. weight on top of it, there will be no doubt remaining that a pressure of 112 lbs. per square inch, which is equivalent to the hydrostatic pressure at a depth of 250 feet, can produce unpleasant effects. Yet we know that divers whose bodies are freely exposed to this pressure, can descend to this and greater depths without hurt or even discomfort. Some people find difficulty in comprehending this. The explanation is that the weight, being a solid body, can exert its pressure in one direction only, viz. downwards. The underside of the thumb is supported by the table, but there is no support round the sides, hence it tends to be flattened, and the distortion causes pain and damage. But water and air are fluids, and, unlike the weight, exert their pressure in all directions at once, so that any object subjected to them is supported on all sides, and if it is incompressible, like flesh and bone, no distortion takes place and no bad effects are produced. The tissues of the body are virtually fluid and therefore there is no more tendency to deform them than there was to deform the sea water which was previously occupying this space. It must be noted that a fluid pressure will only be harmless if it can get at all parts of the body. If any one part, say, a limb, were shielded from pressure to which the rest was exposed, then all the liquids in the exposed parts would be squeezed and driven towards the protected part, which would swell and burst.

If such a thing as a plum or grape be lowered into deep water and pulled up again, its delicate skin will be found to have sustained no damage because the watery contents are incompressible, and no distortion can take place, but if an empty airtight tobacco tin be lowered, it will be crushed by the pressure, because the air it contains is compressible and yields when the pressure is transmitted to it through the thin tin walls. Similarly, if there were any sealed-off parts of the human body containing gas or air, they would be crushed by the outside hydrostatic pressure, but such spaces as do exist are open to the outside air through the nose or throat, and if that air is at the same pressure, they get internal support, and no damage is done.

General Description of the Construction and Working of a Diving Apparatus. A set of the ordinary apparatus consists of seven principal items. (1) A helmet with corselet. (2) A waterproof diving dress. (3) Sufficient length of strong flexible air pipe. (4) A pair of weighted boots. (5) A pair of leaden weights for back and breast. (6) A breast-rope or life-line. (7) An air pump. The helmet, different types of which are described in Chapter 3, is screwed to the corselet by means of an interrupted thread, and the corselet in turn is clamped tightly to the thick rubber collar of the diving dress, which covers the whole body except the hands, which project through elastic cuffs, making a watertight joint at the wrists. Air is pumped to the diver through the pipe and a non-return inlet valve to which it is screwed at the back of the helmet. The air escapes by a spring-loaded outlet valve (at the side of the helmet), which can be adjusted by the diver; this arrangement ensures that the air in the helmet remains at a pressure equal to, or slightly greater than, that of the water at the level of the outlet valve. The helmet, being light and full of air, is buoyant, and the diver could not descend or stand firmly on the bottom were it not for the lead weights of 40 lb. apiece which are carried on the back and front of the corselet. The lead-soled boots weigh about 16 lbs. each. The total weight of the equipment which the diver wears is about 175 lbs. (for particulars of displacement, etc., see Chapter 16). Besides the air-pipe, the diver has connecting him with the surface a "breast-rope", usually with telephone wires running in its interior. He generally descends to the bottom by a "shot rope" attached to a heavy weight which has been lowered previously.

Balance of Pressure on a Diver. We are now in a position to examine the connection between the pressure of air inside a diving dress and the pressure of water outside it. In the first place, it will be realized that when a diver of ordinary height is standing upright, the hydrostatic or water pressure on his boots will be about 2½ lbs. greater than that on his helmet. A diving dress has essentially two portions, a compressible dress and an incompressible helmet. As the diver descends, the pressure increases and tries to squeeze the air out of the dress into the helmet. If we wish to keep the upper part of the dress over the man's chest inflated, air must be pumped into the helmet and the upper part of the dress until the pressure of air in the dress is equal to that of the water at the level of his chest. As the man breathes the air gradually becomes foul; fresh air must, therefore, be pumped in for him to breathe. If no outlet were provided for the air from the dress, the pressure inside the dress would get higher and higher, and there would be more pressure inside the dress than outside it, which for several reasons would be very objectionable. An outlet valve for this surplus air is therefore fitted. This outlet valve works so that when the pressure inside the valve is greater than that of the water outside the valve, it is forced open and the extra air escapes. At first it seems as if the proper place for this valve would be at the same level as the man's chest, since it is the pressure at that level which is required in the dress;

but many practical considerations lead to placing the valve at the side of the helmet. Since, when the man is standing upright, this spot has a pressure about ½ lb. less than exists at the man's chest, a spring is fitted to keep the valve shut until the pressure

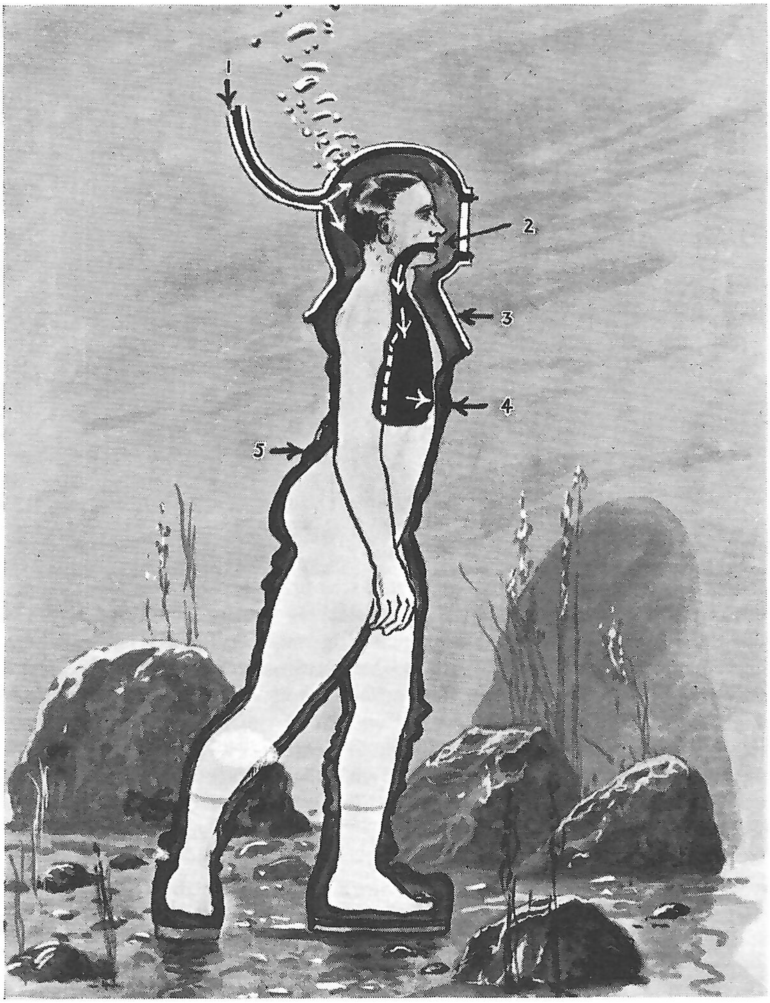


Fig. 19. Diagrammatic section of diver under water *Copyright*

1. Air coming from the pump must be at a pressure equal to that of the water round the diver. so as to inflate the dress and make breathing possible.
2. Pressure of air in the lungs is the same as the pressure of air in the helmet.
3. Rigid helmet and Corselet.
4. Pressure of water (through dress) on outside of chest is balanced by equivalent air pressure inside.
5. Flexible dress.

inside has risen about ½ lb. above that of the water outside; by this means air is kept in the dress over the man's chest, although the valve itself is a little nearer the surface of the water. This valve can be adjusted by the diver to suit his convenience. This is very necessary, since a diver often lies down, when the relative depths of his chest and the valve are altered. Also, it makes a great difference to the diver if the right inflation

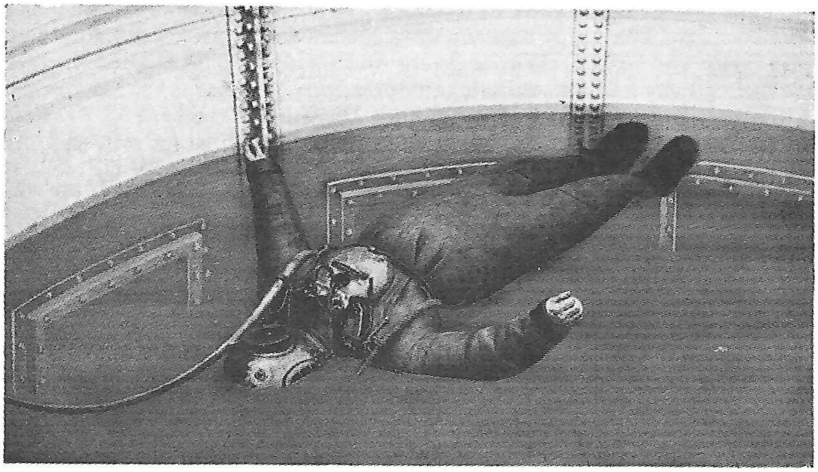


Fig. 20. Diver wearing dress with unlaced legs blown up horizontally in one of Siebe, Gorman & Co.'s experimental tanks

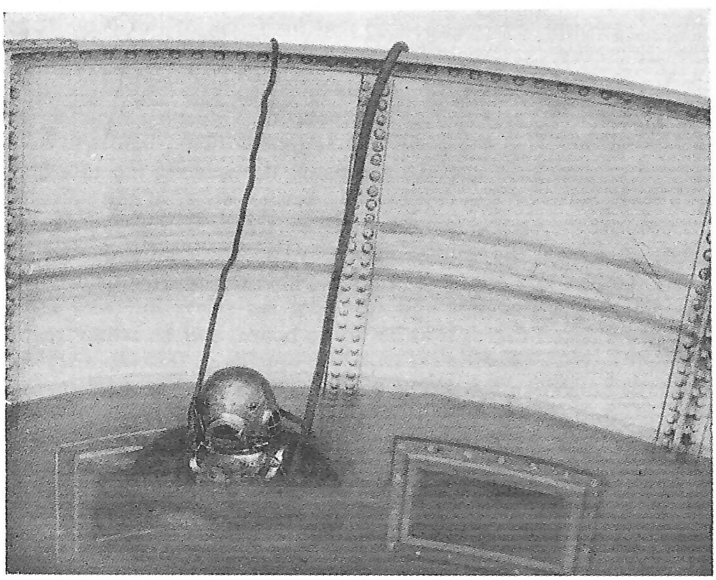


Fig. 21. Diver wearing dress with laced legs blown up vertically

of his dress is obtained. If the dress is too much inflated, he becomes uncomfortably buoyant, and if too little inflated, the weights bear heavily on his chest. It, moreover, reduces exertion, when breathing inside a small space, to have an elastic bag attached to it, like the inflated part of the dress, than to breathe inside such a space with rigid walls like the helmet alone, since the elastic part "gives" to each breath and keeps the pressure constant. The lungs also, are only designed to work comfortably when the pressure inside and outside them is exactly the same; very little additional pressure outside them greatly increases the labour of breathing. As regards the remainder of the body, the pressure of the air at the mouth is instantly transmitted to the whole interior of the body. So that whatever depth the diver may be in, provided a proper air supply is maintained, the pressure outside the body can never be more than a pound or two over that inside the body.

Falls Under Water. It must be remembered that air cannot be supplied to the inside of the dress by the pumps at more than a certain rate; hence, if for any reason a diver changes his depth at a greater rate than that at which the pumps can supply him with the proper pressure, he may be subjected to a very dangerous squeeze from the water.

Suppose a diver at work on a stage, cleaning a ship's bottom, slips off the stage and falls 33 feet owing to carelessness on his part and neglect on the part of his attendants to hold on to the life-line and air-pipe. At this depth the absolute pressure is twice as much as it is close to the surface, so by the descent the volume of the air in his dress is halved. He has an additional pressure of nearly 15 lbs. suddenly applied to every square inch of his body, or about 2,000 lbs. to every square foot, but the pumps will not have had time to raise a corresponding air pressure in the helmet. As the helmet is rigid, his body will be crushed into it with overwhelming force. He may be killed, he certainly will be severely injured, and there will be bleeding from the lungs, mouth, nose, etc. If, however, the diver is at 169 feet, and falls 33 feet, pressure has only increased in the proportion of seven to six, and the volume of air has only diminished by less than one-seventh of its volume, so that the effect will be proportionately less. From this it follows that the deeper a diver, the less serious is a fall.

Blowing Up. The danger in falling is due to the sudden diminution in the volume of the air; sudden ascents may be just as dangerous. One special danger of a sudden ascent is associated with the absorption of air by the blood, and will be considered later. A diver in preparing to ascend tightens up the valve to increase his buoyancy, and allows himself more or less to float up the shot rope. If the valve is closed so tightly as to prevent the escape of excess air, his ascent will at first be gradual; but with each foot of ascent, the volume of air in the dress expands and his speed is quickened. At first the limbs are more or less capable of movement, and the diver has a chance of holding on to the rope and adjusting his valve; but very soon the dress becomes so much inflated that it is as hard as a board, and he cannot reach the valve and is powerless. A diver blowing up from the bottom in this way may smash in his helmet against the bottom of the diving craft, or get badly foul of her moorings. If the dress were to give way anywhere near the head under the strain (which, fortunately, is very unlikely, since the air always escapes through the cuffs), the diver might be in a worse predicament, for, if the attendant failed to haul in the slack of the life-line quickly enough, he might sink again like a stone and be crushed by the pressure due to the depth he had fallen.

Pressure on the Ears. One other effect we have to notice is the pressure on the ears. The ear may be compared with a cavalry drum, which has a parchment covering at one end only. If we were to place such a drum in a recompression chamber, and pump in air, we should very soon find that the head of the drum was being forced in, but if we made a hole in the body of the drum, there would be no change, since the pressure on the inside would always be equal to that on the outside. The condition of the ear is the same as that of the drum. The middle ear (see Fig. 22) is the body of the drum, and across one end is stretched the "drum" of the ear; at the other end is a tube (the Eustachian tube) which leads into the nose and allows the air pressure on the inside of the ear to become equal to the pressure outside. But often, from a slight cold or other cause, the tube leading to the nose becomes blocked up, and we have pains in the ears until the passage is cleared. In the case of a diver this is best done by stopping up the nose and blowing, as described on page 109, or by swallowing his saliva, as the action of swallowing opens the tube. If he cannot open the tube, he must come up again. Usually if the diver can reach five or six fathoms, he will have little difficulty in attaining greater depths, where the relative differences in volume of the air become less and less. Recent investigations during the war emphasized that a diver should "clear" his ears continuously while the pressure is increasing and not wait until he feels discomfort. By this means the difference of pressure between the cavity of the ear and its delicate lining is kept at a minimum. If the diver only occasionally "clears", the lining of the ear becomes congested, and such minor injury, repeated over a period, may cause slight but permanent changes in the hearing. Damage to the ear-drum may also be caused by the pressure of the air breathed, and, therefore, of the air in the Eustachian tube, exceeding that on the outside of the drum. This may cause an outward rupture, commonly known among divers as "Reverse Ears". It can be brought about by the closing off of the outer ear by a close-fitting flexible hood, or by the use of cotton wool or other forms of ear-plug.

1. Eustachian tube connecting the middle ear and the back of the throat.
2. The inner ear where hearing and balancing apparatus lies in bone and is not concerned in pressure changes as it contains no air.
3. Outside air pressure on drum will bulge it inwards towards the air cavity of the middle ear unless a balancing pressure can enter this air space through the Eustachian tube.
4. Ear drum lying between outer ear and middle ear.
5. If the Eustachian tube is clear and open, the air pressure can pass through it from the throat to the cavity of the middle ear.

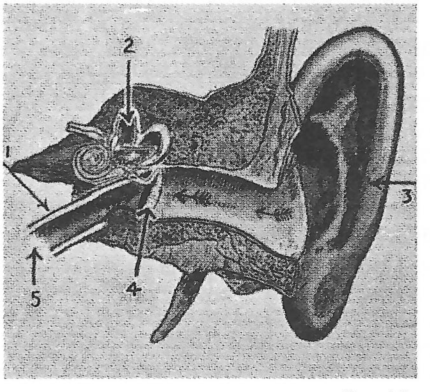


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Fig. 22. Diagrammatic sketch showing how the pressure of air on the ear drum is balanced

We saw that the density of the air increases with the pressure; this leads to certain effects in connection with the voice, which at very great depths has a "Punch-like" quality, which is very distinctly noticed through the telephone. A diver cannot whistle when in deep water, as the density of the air hinders the vibration of the lips.

Breathing and Respiration. Just as a fire needs a draught, so does the body require a supply of fresh air to keep up its activity. When breathing fresh air at atmospheric pressure, the breath we take in (inspire) has the composition, roughly, of

Oxygen: 21 per cent; Nitrogen: 79 per cent; Carbon Dioxide: ·03 per cent.

But the breath we breathe out (expire) is composed, roughly, of

Oxygen: 16 per cent; Nitrogen: 80 per cent; Carbon Dioxide: 4 per cent.

So that, in the short time one breath remains in our lungs, about 5 per cent of its oxygen is taken away, and about 4 per cent of the rather poisonous gas, carbon dioxide, is added to it for discharge to the outside.

CARBON DIOXIDE

Carbon dioxide (CO_2) is the natural stimulant to breathing which is so regulated as to keep the percentage in the depths of the lungs at about 5·5 per cent of an atmosphere and its partial pressure at about 40 mm. Hg. At 5·5 atmospheres, the percentage in the alveolar air* is 1·0, as shown by experiments on themselves in a Siebe, Gorman experimental chamber by Leonard Hill and Greenwood.

The gas is constantly produced by the oxidation (burning) of sugar (the fuel) in the body to supply the necessary energy for the maintenance of body heat, movement of muscles and the proper functioning of the various organs. It is carried from the organs to the lungs by the blood in the veins which, with its reduced content of oxygen, is able to transport more CO_2 than the fresh arterial blood.

The effect of the constant respiratory movements—inspiration and expiration—is to ventilate the lungs and to remove any excess of CO_2 liberated from the venous blood as it passes through the lungs. When more CO_2 is produced by oxidative processes as the result of hard work, we breathe harder to get rid of the excess and to keep the normal amount in the depths of the lungs and in the blood. A man running hard will produce ten times as much as he does when resting in bed. If extra work is done, more fuel is burnt and more CO_2 liberated. The CO_2 further stimulates the centres that control breathing and thus the excess is removed by ventilation. The washing out of the lungs is best effected by increasing the depth of the respirations, and not by increasing their frequency. If, when a diver is in deep water, the rate of his respiration is counted, it will be found to be the same as when at the surface, provided the air supply is adequate. If a person holds his breath, he is finally forced to breathe because of the extreme stimulation by the CO_2 he has accumulated. If he breathes oxygen or air which contains more than the normal amount of CO_2 his lung ventilation, as we have already said, will be increased, and in some cases an actual tonic effect may be felt, due probably to improved circulation in the brain.

Danger of CO_2 at the Surface. The popular idea of the danger of CO_2 in the air is much exaggerated. In fresh air there is only ·03 per cent of CO_2 and if we are resting at ordinary atmospheric pressure, it is not until we get this percentage increased a hundred times that we begin to feel its effects in any way. When this percentage (3 per cent) is reached, we breathe about twice as deeply as we do usually. At about 5 or 6 per cent there is severe panting and a person will become confused. At 10 per cent there is extreme distress and the gas exerts an anæsthetic effect, the person becoming flushed and dissociated. At a slightly higher percentage loss of consciousness occurs, which at about 25 per cent may prove fatal.

Effects of CO_2 under Pressure. Whilst it is true that the effect of a small percentage of CO_2 at normal atmospheric pressure is harmless, it was found by the late J. S. Haldane and J. G. Priestley that it does not hold true when the air is under pressure. In this case, to estimate the effect of the CO_2 the percentage present must be multiplied by the absolute pressure, when the effect on the human body will correspond with that produced by the new percentage at normal pressure. For instance, at 33 feet 1 per cent of CO_2 has exactly the same effect as 2 per cent has at the surface, or as 0·5 per cent would have at 99 feet. In other words, the deeper the diver descends the greater is the effect of a small percentage of CO_2 in the helmet.

In deep-sea diving, CO_2 may become a serious menace to the diver in certain circumstances. For example, if his air pipe be cut, or his pump fail (both rare occurrences) he does not immediately die, as some people think, for the air inlet valve in his helmet closes at once and keeps the air pressure in his dress. His time of safety now depends upon the rate of accumulation of CO_2. If he keeps quiet and steady, he will have a minute or two in which to extricate himself. As soon as he is able to start rising to the surface, the expansion and venting of the air in his dress will reduce the tension of CO_2 and he will survive.

In earlier days, CO_2 intoxication was often experienced because the diver was not receiving enough air from his pump. It was not appreciated that the efficiency of

* The alveolar air is collected by breathing out through a long tube and taking a sample from the tube near the mouth at the end of expiration.

helmet ventilation was proportional to the volume of air delivered at pressure equal to the diver's working depth. Thus, at 300 feet of sea water—10 atmospheres absolute, ten times as much air is needed as at one atmosphere absolute. Recently it has been shown that the more alarming effects of Nitrogen Narcosis (see page 14) are caused by CO_2 accumulating in the helmet. To obviate the dangerous intoxication and even loss of consciousness sometimes experienced by divers at the greater depths, it has been found essential to keep the partial pressure of CO_2 down to at most 2 per cent of one atmosphere, and an even lower figure is desirable when possible.

These problems have been solved by local circulation and purification of the air in the deep-sea diver's helmet (see Chapter 7).

In self-contained diving apparatus on Siebe, Gorman & Co.'s original regenerative principle, using carbonic acid absorbent and pure oxygen, or special mixtures of oxygen and nitrogen, or of oxygen and helium, CO_2 should not accumulate provided the apparatus is properly maintained and serviced. Those responsible should know the life of the CO_2 absorbent canister; the golden rule is, "If in doubt, recharge it". Attempted economy in such matters is dangerous. A faulty canister is usually indicated by the user's increased rate of breathing. It has been suggested that men who are going to use this type of apparatus should have experienced (under competent supervision) CO_2 accumulation by deliberately wearing an apparatus with an exhausted canister, so that they might quickly recognize what is wrong should the adverse effects occur in more dangerous surroundings.

We emphasize later (see page 315) that, when breathing oxygen and working hard it is impossible to notice the stimulating effect of any CO_2 present; extra care must therefore be taken if hard work is anticipated, since CO_2 accelerates the onset of oxygen poisoning. As, however, most oxygen diving is confined to shallow depths, danger from this cause is unlikely. If, however, divers are to breathe oxygen at the 60-feet stage during decompression after deep dives, great care must be taken that they are not previously exposed to a raised concentration of CO_2. Men sealed in a confined space such as a submarine compartment without air regenerating means, will gradually use up the oxygen and produce high concentration of CO_2. The danger of flooding foul compartments of submarines and suddenly increasing the pressure of CO_2 is discussed in Chapter 14.

Finally, the "off-effect" of CO_2 must again be mentioned. If a person has been breathing considerable amounts of the gas for a long period, the resumption of breathing air after pure oxygen will cause severe headache. Some will also suffer nausea and even vomiting. This matter is very important in submarine escape, in connection with which exposure to high concentrations of CO_2 must be avoided if at all possible, since nausea and vomiting, as shown by J. B. S. Haldane, will make oxygen breathing very difficult, if not impossible.

Air Supply required by Diver. It will be seen that the danger from the accumulation of CO_2 in the dress is not an imminent one, and the pumps can usually be stopped for three or four minutes before the CO_2 accumulates to a serious extent, and if the diver is ascending, for much longer. How much air does a diver need? We saw that when CO_2 reached 3 per cent a man at rest at ordinary atmospheric pressure feels it. If he is working, 3 per cent will cause him distinct discomfort. From a very large number of analyses of air issuing from the divers' helmets Haldane found that they produce about ·014 cubic feet of CO_2 (measured at atmospheric pressure) in one minute when at rest on the bottom at all depths, and about ·045 cubic feet (measured at atmospheric pressure) when at work. From this it can be calculated that, during ordinary work, an air supply of 1·5 cubic feet per minute, measured at the existing pressure, will prevent any serious accumulation of CO_2 in the helmet. This volume of air will be needed at all depths, so that we can estimate what pumping power is required in any given circumstances. Speaking roughly, one Siebe, Gorman British Admiralty type double pump will serve a diver up to 17 fathoms; beyond that, two such pumps have to be connected to his air-pipe, and at depths beyond 30 fathoms, three are required.

TABLE III

Quantity of air (ventilation) required by a diver at various depths

Depth in fathoms	Feet	Quantity of air at atmospheric pressure required per minute Cubic feet	Number of cylinders needed of Siebe, Gorman & Co's patent double acting pumps (hand-worked)*	Revolutions of the pump per minute
0	0	1·5	1	15
2¾	16	2·2	1	22
5½	33	3·0	1	30
11	66	4·5	2	22
16½	99	6·0	2	30
22	132	7·5	4	21
27½	165	9·0	4	27
33	198	10·5	6	23
35	210	11·0	6	28
38	228	12·0	Hand-worked pumps are not suitable for these depths	
44	264	13·5		
49	294	15·0		
53½	321	16·2		

* Two-cylinder Admiralty type pump.

With such an air supply the diver need never fear any shortage of ventilation and, therefore, accumulation of CO_2.

The Absorption of Gases by Liquids. When a gas is in contact with a liquid on which it has no chemical action it is absorbed by the liquid in amounts which are proportional to the pressures under which the gas is at the time. In the lungs we have the blood practically in contact with the air. In the air we have three important gases—oxygen, nitrogen and CO_2. Of these the nitrogen alone can remain and accumulate in the blood. It is not to be supposed that the oxygen and CO_2 are not absorbed by the blood under pressure, but the oxygen is used up in the tissues and the breathing prevents the pressure of CO_2 from ever increasing, so that the only gas which accumulates in abnormal quantity in the blood when the diver is under pressure is nitrogen.

When gas is forced into a soda-water bottle under pressure, the water appears to be unchanged so long as the pressure is kept up, but the moment we reduce the pressure, by taking out the cork, we see the gas come bubbling off the liquid.

Cause of Compressed Air Illness. Applying the analogy to diving,† the diver is the soda-water bottle and his blood is the fluid in the bottle. As the diver descends, nitrogen under pressure comes into contact with his blood. The blood takes up the nitrogen from the air. So long as he stays below under that pressure, his blood appears to be unaltered; when, however, he ascends, the excess of nitrogen that the blood has taken up may begin slowly to bubble off; if the blood were as fluid as water, it would come off as rapidly as from the soda water. Fortunately for the diver, the blood is a thickish, albuminous fluid, in which bubbles do not readily form, and, as far as we can see, it can retain about twice as much gas in solution as water can at any given pressure. The lining and shape of the blood-vessels also discourage bubble formation. Every diver knows that it is quite safe to come up from a depth of from five to six fathoms to the surface as quickly as he likes; the reason for this will now be easily understood, since at such a depth the blood has only twice as much nitrogen in it as it has on the surface, and therefore bubbles are unlikely to form. If, however, the diver has been for any considerable time at 30 fathoms and then comes up quickly, it is almost certain that bubbles will form and cause the serious illness which is known as "Compressed Air Illness" or, less correctly, as "Caisson Disease".

† Professor de Mericourt, page 4

Not only is the air taken up by the blood, but the tissues of the body also gradually get saturated with it. In the case of the blood, the saturation is very quick; it is probable, indeed, that the blood leaving the lungs is always saturated to the existing pressure, but the tissues take up the gas at a much slower rate—a rate which depends on the blood supply. Where this is good, as in the brain and spinal cord, the saturation is quick, but in the fibrous tissues about joints, etc., saturation is very slow. Those tissues which are saturated quickly also give up their surplus nitrogen quickly, and those which saturate slowly also desaturate slowly.

It is fortunate that the tissues of the diver take so long to get saturated with the air, as it much reduces the dangers due to short stays under water. The Greek divers will come up from 30 fathoms as fast as they can, but they make very short stays under water; their time from surface to the bottom and return does not exceed ten minutes, so that their tissues are not sufficiently saturated to cause danger unless they make successive dives at short intervals of time.

Forms of Compressed Air Illness. The following briefly are the effects likely to result from the formation of bubbles in the blood and tissues. In the first place, they may come off in the blood-vessels themselves, filling the right side of the heart with air, and causing death in a few minutes. In less sudden cases the bubbles form in the spinal cord, leading to paralysis of the legs (diver's palsy), whilst in less serious cases we may only have severe pains in the joints and muscles, called "bends". (See also Chapter 6.)

How to Avoid the Danger. In the first place, the time spent under pressure must be limited according to the depth, and, though the diver may go down as quickly as practicable, his ascent must be strictly controlled in the way described on pages 96-97, and in accordance with the tables printed on pages 100-108.

In ascending, the diver is decompressing himself, and it is this gradual decompression that is the most important factor in the prevention of accidents from the formation of bubbles of nitrogen. The blood, we saw, could hold in solution about twice as much of the gas at any pressure as it would do if it behaved like water; we can therefore come up from 33 feet to the surface without fear of ill effects. This relative amount of two to one of absolute pressures holds good up to fairly high pressures,* so that the diver at seven atmospheres (198 feet or 33 fathoms) can come quickly up to three-and-a-half atmospheres (82 feet or 14 fathoms), or when at six atmospheres (165 feet or 27½ fathoms) to three atmospheres (66 feet or 11 fathoms) without danger of bubbles forming. It will be seen how very important this law is, for the diver can come up quickly from the dangerous depths to a depth within reasonable distance of the surface. After the first long stage, the subsequent stages must be taken with frequent pauses in order to let the excess of nitrogen pass off through the lungs, the longest pause being made a few feet below the surface. It need hardly be stated that the time of the pauses must be signalled from the surface, as, naturally, the diver has very little notion of time.

It was formerly considered beneficial for divers to exercise during their decompression, so as to hasten the elimination of nitrogen from their bodies. It was believed that this would decrease the risk of bubble formation, but experience has proved the reverse. This unexpected result may be accounted for as follows:

Firstly, the rapid stripping of the blood and fluid parts of the body will reduce the tension of nitrogen in areas immediately adjacent to the slower desaturating areas and this large gradient may well be more favourable to bubble formation in these regions. Exercise also causes considerable changes in the chemical and gaseous equilibrium in the body and there will be increased turbulence in the blood-vessels. This latter factor is known to be favourable to bubble formation. The Medical Research Council

* It is not certain that the 2-1 ratio holds good at the very great depths now reached by deep divers, and in some parts of the deep diving decompression tables a ratio of 1·75 to 1 has been used.

workers exercised vigorously on decompression during their war work, and the incidence of "bends" was so high compared with the naval workers at Siebe, Gorman & Co.'s (A.E.D.U.) who did not exercise, that it was abandoned. In low pressure work, both the Canadian and the U.S. Navies have shown conclusively that exercise while in danger of "bends", greatly increases the incidence both in men and animals.

With regard to increased CO_2, it is now generally considered that this may also increase the incidence of "bends". This impression has been supported by the reduction in "bends" by the improved circulation in the helmets.

Recompression. Sudden change of weather or other emergencies sometimes necessitate divers being brought up from the bottom too rapidly, and in this and other ways cases of compressed air illness may arise. An almost certain cure is available if the sufferer can quickly be subjected to pressure in a recompression chamber. Practical details are given in Chapter 6, and it suffices to say here that the effect of such treatment is to cause the disappearance of the bubbles causing the illness.

A recompression chamber may also be used as a preventive of compressed air illness in the case of a diver who has blown up, and in certain kinds of work its presence enables the diving to be speeded up in a way that would not be justifiable if the means of curing compressed air illness were not at hand.

Oxygen Breathing. The time required for safely decompressing a diver can be greatly shortened if arrangements are made for him to breathe oxygen during his ascent. The special methods used in deep diving are described in Chapter 7. Oxygen breathing apparatus may also be used in conjunction with the recompression chamber, as described in Chapter 6, and men who are specially liable to "bends" can prevent them by breathing oxygen from a portable apparatus such as the "Novus" for 20 minutes or so after reaching the surface and undressing. This procedure has been carried out as a routine in certain important salvage operations.

Selection of Divers. They should be steady men of good physique and capable of enduring considerable bodily and mental strain. If possible, men who have a strong team spirit and an alert sense of responsibility should be selected. The "lone-wolf" is never a success in the diving world, either below or above water. They should be medically examined to ensure that each candidate is free from any organic disease, particularly of the heart and lungs. Any past history of serious cardio-respiratory disorder that may have left any residuum, should disqualify, even though the present health may appear excellent.

Any nose or throat abnormalities or disease, unless easily remediable, should disqualify. Any candidate with middle ear disease or deafness should also be rejected. There should be no history of nervous breakdowns, irresponsible behaviour, or fits. Addiction to alcohol is also undesirable, as it indicates mental instability and inability to stand sustained mental or physical strain. Heavy smokers are not usually suitable, although the younger age groups are little affected by this habit. Nevertheless, they should be asked to keep their smoking within reasonable limits.

As a general rule, men over 30 years of age should not be selected for training as divers. Trained divers can continue for some years after this age, but must be watched carefully as they enter their late thirties. Divers beyond the age of 45 ought not to be employed on deep diving or in any work involving long stays under pressure. Men who are overweight should be rejected. It is said that they are more prone to bends, but what is more important is that they are not fit for arduous diving. Any chronic skin condition should exclude the candidate. Even innocuous conditions like psoriasis are undesirable, for obvious aesthetic reasons.

Diving should not be attempted immediately after a heavy meal; time should be allowed for its digestion.

No man should dive if he is not absolutely fit. Even minor complaints (sore throat, common cold) should be reported, and the diver stood off. If possible, divers should be examined by a doctor before any deep or arduous diving project.

Finally, physical examination of the chest is not adequate, and all candidates should have their chests X-rayed, and passed, before being accepted and allowed to go under pressure. Routine medical examination, including pulmography, should be carried out at least once a year.

As detailed earlier, all candidates should also be tested in a pressure chamber while under close observation.