SUBMARINE ESCAPE BREATHING AIR

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(With 4 Figures in the Text)

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Recent research has even further emphasized the physiological dangers to which man is exposed when breathing gases at increased tensions. If he breathes air his activity under water is greatly limited by the problems of supply and compressed air illness. The latter is due to the formation of bubbles of nitrogen in the body on return to normal atmosphere. If he breathes oxygen, then he is in grave danger of oxygen poisoning, with convulsions, even at relatively shallow depths (Donald, 1947). During the recent war, mixtures of nitrogen and oxygen were employed for important work where the diver wished to go to considerable depths while carrying his own gases. These mixtures were varied in composition and rate of supply so that oxygen poisoning was avoided, and immediate rapid surfacing was possible, without compressed air illness occurring. However, this ingenious compromise is limited in its application, for as greater depths are reached, the oxygen has to be greatly reduced to avoid convulsions. The resultant rise in the proportion of nitrogen being breathed causes bubble formation in any but the shortest exposures. It is to be doubted whether the maintenance and meticulous supervision required, when using mixtures, will allow the use of these in the more normal conditions of peace-time. It has become increasingly apparent that the prolonged underwater survival of men requires pressure-withstanding devices in which he can exist at normal physiological tensions, i.e. atmospheric pressure. The rigid diving suit and submersible chambers, such as the bathysphere, are in their infancy; but the submarine, where the same conditions apply, is now a highly successful and developed method of underwater existence and locomotion. The further evolution of these devices, and of the submarine, depends mainly on engineering advances and not upon attempting to extend the comparatively rigid limits imposed by human physiology. The maintenance of a healthy atmosphere within a submarine is again a chemical and engineering problem which is capable of solution and constant improvement.

However, one great problem, which is still imperfectly solved, is the escape of personnel from sunken submarines. In order to leave the submarine the men must be temporarily exposed to the full pressure at which the submarine is lying. The essence of the problem is how to do this with a group of men with minimum physiological risks, minimal demand on already highly strained and exhausted personnel, and the avoidance of a single failure to escape jeopardizing the chances of the remainder of the group. Let us briefly survey the present methods of escape and review their advantages, disadvantages and dangers.

Twill-Trunk method

This method and its variants depend upon the flooding of a complete compartment of the submarine. A collapsible, hooped, trunk of rubberized cotton twill is fitted below the escape hatch. Before escape is possible this trunk must be extended so that its lower entrance is near the deck. It is then stayed down. The compartment is deliberately flooded through special valves until the pressures of air and water in the compartment are equal to the sea pressure outside the submarine. It is now possible for one man to dip under the trunk, and to open a vent valve in the hatch, thus releasing the air in the trunk and flooding the latter with water. The air-lock in the compartment is maintained and survivors can now in turn, don their breathing apparatus, dip under the trunk, and escape through the hatch to the surface.

The breathing apparatus employed contains oxygen which, under favourable conditions, and at moderate depths, is only breathed at increased tensions for a very brief while, and oxygen poisoning is therefore unlikely. The flooding of such compartments take from 15 to 20 min. and, at moderate depths, the average pressure during that time is unlikely to be dangerous with regard to nitrogen bubble formation after escape. The breathing of oxygen after this exposure also accelerates the elimination of nitrogen (Bert, 1878; v. Schrötter, 1906; Bornstein, 1910; Admiralty Diving Committee, 1933). The important advantage of this method is that the whole group of men are together until the moment of escape, which only takes a few seconds, and no further manipulation is needed. Thus discipline and morale can be maintained, and instruction and encouragement given by senior personnel. Persons who are unfortunate enough not to survive the escape are not seen by those awaiting their turn.

Apart from the question of morale, however, this method has little to recommend it. Many conditions exist which, severally or together, may render this method extremely hazardous. It is possible that the submarine may land at an angle which renders the formation of an effective air lock impossible. Leaks in the hull will also cause the loss of air. Leaks into other compartments will greatly prolong the time of flooding and increase the risks of compressed air illness. At greater depths the physiological hazards become enormously increased. If the tension of carbon dioxide is raised in the submarine owing to a long dive or incomplete air purification, the compression of this air will considerably increase the partial pressure of carbon dioxide. As the flooding proceeds, breathlessness, panting and confusion will develop gradually but inexorably. If the tension becomes high enough, unconciousness will ensue. Below about 200 ft., the increase of nitrogen tension in the atmosphere will also cause intoxication with mental retardation and instability. Case & Haldane (1941) have shown that, under such conditions, carbon dioxide causes less hyperpnoea, and unconciousness occurs with less warning and at lower tensions. Other toxic gases or fumes will not only increase in partial pressure, and resultant toxicity, but even greater absorption will occur with the increased pulmonary ventilation caused by the raised tension of carbon dioxide. A simple example will emphasize the danger of compressing foul air. If a submarine, in which there is 3 % carbon dioxide, is flooded to a pressure of 132 ft. of sea water (5 atm. abs.) the partial pressure of this gas will be 15 % of an atmosphere, which would rapidly cause unconciousness. The period during flooding, whilst symptoms of carbon dioxide stimulation and intoxication are developing, would be most demoralizing in a group of men under such trying circumstances. It is obvious that these men, in order to avoid these symptoms, will start to breathe oxygen, as the only alternative, at various stages of such a compresssion, and, unless a definite order were given, there would be much uncertainty and confusion. The breathing of raised tensions of carbon dioxide also causes 'jitteriness' and tremulousness, a fact that can be easily demonstrated in rebreathing experiments. Another hazard is the 'off effect' of carbon dioxide when the assumption of oxygen breathing after breathing raised tension of this gas, causes severe vomiting and headache in a certain percentage of people (Haldane, 1939). The oxygen-breathing apparatus may be rejected as a result of this and the person is re-exposed to the poisonous atmosphere.

In the event of the air being respirable after flooding, the risks of severe compressed air illness after such exposures is very great, and probably increased by the raised tensions of carbon dioxide. These risks have not been accurately defined but evidence accumulates (see later) that they are very grave indeed. If the air is not respirable and oxygen breathing is adopted, then oxygen poisoning is a serious menace. Haldane (Case & Haldane, 1941) convulsed after breathing oxygen for less than 5 min. at 200 ft. In many cases oxygen would be breathed during the later and slower stage of flooding and personnel would be exposed to this risk for a number of minutes, particularly if they were among the last to leave.

Under such conditions, despite careful training, men are inclined to be clumsy and apprehensive with even the most simple apparatus. The greater the pressure the more gas is needed to fill the counter lung and there may be a real risk of running out of oxygen, particularly from unnecessary 'by-passing'. They may escape without opening the exhaust valve of the breathing bag, which has been shut to conserve oxygen. During the ascent this will cause a rapid and fatal rise of intra-pulmonary pressure. Others leave the mouthpiece cock shut, despite the fact that it renders them unable to breathe. Oddly enough, a number survive who do this as there is no desire to breathe in, owing to the expansion of gases in the lungs during the ascent. After the *Thetis* disaster, attempts were made to develop respirators that would absorb the carbon dioxide but allow the breathing of air and accept the risk of bends. A large series of experiments was also carried out by one of the authors at the Admiralty Experimental Diving Unit during the war. In the latter experiments, attempts were made to adapt the oxygen-breathing apparatus so that it could be used as a CO_2 respirator as well. Separate CO_2 respirators were also developed. All these attempts were unsuccessful, as in the tensions of CO_2 anticipated, enormous canisters were needed to absorb efficiently the carbon dioxide for any period of time. Even when this was obtained, the heat developed, despite coolers, finally made breathing impossible. It became clear that this approach was impracticable.

In conclusion, the 'twill-trunk' method of escape is a useful procedure only when the depth is not great and when the air of the submarine is respirable after compression. Such conditions are unfortunately rare.

Chamber escape

In this method chambers are constructed in the bulk-heads of the submarine. They have pressure hatches opening to the compartment on either side, and also to the exterior. In order to escape, the men enter the chamber which is then shut off from the main compartment, while the remainder continue to breathe air at atmospheric pressure. Thus the dangers of submitting a group of men to compressed foul air over a moderately prolonged period are avoided. The escape chamber is then flooded either by those in the chamber or by those remaining in the compartment. It is a rapid and complete flooding, the air in the chamber being vented outboard. The escaping personnel wear their oxygen breathing apparatus from the beginning of flooding. This can be carefully checked by the appropriate officer or rating, if necessary, and the errors already mentioned avoided. They thus avoid the dangers of a sudden rise in CO_2 tension, and are only exposed to high pressures of oxygen for less than a minute. The hatch opening to the sea is also under dual control and is opened as soon as the chamber is flooded and the pressure equalized. They can then escape. The hatch, through which they escape, is then closed by those remaining in the submarine, the chamber drained into the bilges, and the whole operation is repeated. There is, therefore, no risk of bubble formation and but little of oxygen poisoning. Ear drums may be ruptured by the rapid increase in pressure, but teaching should strongly emphasize that such an accident is trivial compared with the issues at stake. This almost always occurs in the early stage of flooding when any tendency to panic caused by the pain, is not so serious as it would be in the later stages.

The chamber escape, therefore, reduces physiological risks to an absolute minimum, and yet, on the whole, this method of escape has yielded the most disappointing results. Its grave disadvantages are not physiological but psychological, and although physiological safety is an absolute necessity, it is of no use if, at the same time, demands are made on the exhausted and highly strained personnel, which they are unable to meet. In the twill-trunk method the whole group remain together while the major procedure of escape, i.e. flooding, is carried out, and, when the hatch has been opened, the way to the surface and safety is open and ready for all without further manipulation. In the chamber method, a not uncomplicated procedure has to be repeated many times, without accident, before the last man escapes. This does not improve morale, which is balanced on razor's edge and 'incidents' are almost inevitable. The time of greatest trial for each individual is the complete and sudden flooding in a closely confined space, frequently in darkness. Such a procedure is most trying to even the most practised and intrepid underwater divers. Panic is therefore almost inevitable in one or more persons in any group. Although the first few escapes are normally carried out by reliable persons to 'show the way' and aid rescue operations at surface, after this there is an obvious tendency to send up those who are least experienced, or near breaking-point. The escaper in panic usually struggles irrationally to keep his head above water, or may tear off his apparatus. As in the panic of drowning, he may seize the other person in the chamber and struggle with him. If this occurs, the chamber has to be drained down again and reopened: a dead, unconscious or hysterical person being returned to the compartment. This can obviously do nothing but grave harm to the morale of the group. It is possible, and indeed probable, that such an accident may cause a decision to employ the alternative method of escape and flood the compartment, with sudden breathing of compressed foul air causing further confusion and tragedy. If the chamber has been completely flooded to full pressure and the persons wish to return to the submarine compartment, the opening of the drain into the submarine will cause a reversion to atmospheric pressure in a fraction of a second, as water is practically incompressible. Thus the gas in the lungs and apparatus will expand at great speed and may severely injure the persons in the chamber. Another important danger is that a casualty may foul the hatch leading to the sea, thus preventing it being shut again from inside the submarine. This renders this route of escape impassable unless the whole compartment is flooded and the chamber is used like a twill trunk.

Submerged chamber escape

This type of escape depends upon the submarine being located in a relatively short time, and a chamber that fits on to the submarine being lowered to it. The rescue of the crew of U.S.S. *Squalus* was performed by this means. The submerged chamber rescue calls for a singularly fortunate series of events—the finding of the submarine, its successful examination by divers, the proximity of a special base and facilities, and finally, favourable weather. As an active service measure, it has no value, and, even if further developed and improved, there must still be a method of escape which can be used in the likely event of no outside help being available.

Present experiments

During experiments, carried out in the Admiralty Experimental Diving Unit, on divers and goats surfacing immediately from air dives of considerable depth, with subsequent recompression and decompression in a chamber, it became apparent that short exposures to air, at considerable depths, may not cause compressed air illness even when recompression is omitted. The dangers of compressed air illness, and carbon dioxide and oxygen poisoning, in the twill-trunk escape, and the psychological disadvantages of complete flooding in the chamber escape, caused consideration as to whether the breathing of ordinary air, right up to the moment of leaving the submarine, was a practical measure. At this stage it had not been decided whether air-breathing apparatus should be worn or not, but if the requisite pressure were partially obtained by compressed air as well as flooding, then the subject need not be totally immersed during a chamber escape, and, even if no breathing apparatus were worn, or available, he may still be capable of survival. Before deciding more detailed practical points a series of experiments was carried out. The most important task was the assessment of the risk of compressed air illness in the exposures to air involved in such an escape from a submarine. Secondly, the problem of nitrogen intoxication at these pressures of air had to be carefully considered.

COMPRESSED AIR ILLNESS

Method

In view of the obvious dangers of these experiments it was decided to employ goats in this first exploratory series. The Admiralty Diving Committee (1907, 1933) employed these animals extensively for decompression studies as they approximate closely to the human in rate of nitrogen absorption, elimination, and susceptibility to bubble formation. A recent series of experiments on surface decompression (Donald & Davidson, 1945), where both men and goats were exposed to similar procedures, has strengthened this assumption. On the whole it would appear that, if a goat is safe after a certain exposure, then there is an even larger margin of safety for men. However, in view of the known variability of susceptibility to bubble formation in all species, this margin of safety is highly desirable. A 100 cubic-foot pressure chamber was employed, and the considerable pressures needed were achieved in a relatively short time by running air sequentially from large banks of high-pressure cylinders. The procedure employed imitated, as closely as possible, the pressure conditions in a submarine chamber escape, with the animals breathing air throughout. It was as follows:

Stage I. Time from atmospheric pressure to full pressure—2 min. (flooding of escape chamber).

Stage II. Time at full pressure—variable (manipulating hatch and emerging from submarine).

Stage III. Average rate of ascent or release of pressure—2 ft. per sec. (ascent to surface from submarine).

These experiments were carried out at pressures representing depths of from 150 to 300 ft. of sea water. The rate of compression was not absolutely 'linear' but approximated to this as new banks of air were employed as the pressure increased. The rate of ascent of men escaping from submarines at depth is not yet accurately known. It will obviously vary with the apparatus and clothing worn. The rate of decrease of pressure in these experiments was proportional to the excess pressure in the chamber. This meant that the simulated ascent was far more rapid at the early stages and slower as the surface was reached. It is known that under escape conditions the rate of ascent is not constant and it is probable that the early part of the ascent is more rapid. However, the conditions of ascent in these experiments were almost certainly somewhat favourable, particularly as regards the development of 'chokes' (asphyxia due to pulmonary air embolism), as the greatest danger is near the surface where a small change in depth causes a much larger change in the pressure ratio than at greater depths. The average rate of ascent of 2 ft./sec. was decided upon as a result of trials by the Superintendent of Diving. The exhaust manifold had to be steam heated in order to prevent ice formation due to the violent release of compressed air. After each experiment the goat was kept under constant observation for 1 hr. and intermittent observation for a further 3 hr. Any animal showing any abnormality was immediately recompressed.

Results

All times stated here are the times at full pressure. The time of compression and rate of decompression were kept as constant as possible, as described above. Details of the times of each experiment are to be found in Tables 1–3.

Exposures to 150 *ft.* Five exposures of 3 min., five exposures of 5 min., and three exposures of 7 min. at full pressure were carried out with no signs of bubble formation, or disturbances of any kind.

Exposures to 200 *ft.* Three exposures of $2\frac{3}{4}$ min., two exposures of 3 min., and six exposures of 5 min. at full pressure, similarly caused no disturbances. 7 min. exposures were not carried out at this depth.

Exposures to 250 *ft.* Five exposures of between 2 and 3 min., five exposures of 5 min., and four exposures of 7 min. at full pressure were carried out. No signs of compressed air illness were observed except in one exposure of 7 min. This goat developed a 'bend' in the right hind leg 12 min. after returning to atmospheric pressure. The animal was immediately recompressed, but on final decompression developed transverse myelitis with flaccid paralysis of the hind legs. This animal was a small female weighing only 44 lb., against the average weight of 80 lb. It is not known what bearing this

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has on the occurrence of bends, but, it is a point worth noting.

Exposures to 300 ft. Five exposures of 3 min., and five exposures of 5 min., at full pressure were carried out. Grave compressed air illness occurred in a number of cases. In the 3 min. exposures three out of the five animals were seriously affected. Two developed 'chokes', which in one case was immediately fatal. The second case was relieved by immediate recompression but developed multiple bends. The third casualty developed transverse myelitis 4 min. after surfacing. Therapeutic recompression was ineffective. In the five exposures of 5 min., three animals were unaffected, one developed a bend in the leg which was cured by recompression and the other developed incurable transverse myelitis 10 min. after surfacing. Details of these experiments are given in Tables 1 and 2 and shown graphically in Fig. 1.

Table 1. *Showing times, in sec., of exposures during various stages of escape procedure at* 150, 200 *and* 250 *ft.*

Goat	Depth (ft.)	Stage I	Stage II	Stage III
1	150	110	190	75
2	150	120	180	75
3	150	120	180	75
4	150	135	180	75
5	150	120	180	75
2	150	120	300	120
6	150	125	295	120
5	150	60	300	72
1	150	60	300	72
11	150	120	300	120
7	150	115	425	120
8	150	115	425	90
10	150	115	425	90
12	200	135	165	110
13	200	135	165	100
14	200	135	165	100
3	200	120	180	120
2	200	120	180	120
15	200	77	300	80
4	200	77	300	80
5	200	230	300	110
1	200	230	300	110
10	200	135	300	125
12	200	135	300	125
1	250	165	135	125
10	250	150	150	125
3	250	150	150	125
2	250	135	165	125
5	250	135	165	125
4	250	125	175	125
12	250	150	300	90
10	250	150	300	90
15	250	90	300	140
4	250	90	300	140
2	250	120	300	120
2	250	120	420	130
1	250	120	420	125
4	250	120	420	125
10*	250	120	420	125

Stage I is the flooding or compression stage (ideal 2 min.); stage II is the time at full depth (opening hatch, emerging and commencing ascent); stage III is that of decompression (ascent from submarine to surface), average rate aimed at 2 ft./sec. No signs throughout the series except in last experiment.

* For details, see text.

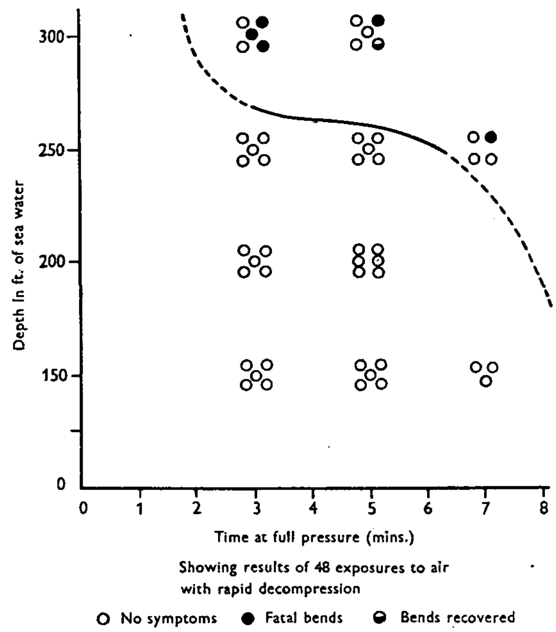

Fig. 1.

Exposures to 300 *ft.* These were carried out using artificial mixtures of oxygen and nitrogen. As the procedure had been comparatively safe at 250 ft. breathing air, the pressure was obtained with a mixture of oxygen and air, giving an analysis of 34 % oxygen and 66 % nitrogen at full pressure. This mixture gives an 'equivalent air depth' of 244 ft. and an 'equivalent oxygen depth' of 80 ft. (i.e. the same tension of nitrogen was present as would occur in air at 244 ft., and of oxygen as in pure oxygen at 80 ft.). In view of the very short exposures there was little danger of oxygen poisoning. In two exposures of 5 min., and three exposures of 7 min. at 300 ft., employing this mixture, there wa no sign of compressed air illness on surfacing (see Table 3).

Discussion

It has been clearly shown in these experiments that short exposures to relatively high pressures of air, with immediate return to atmospheric pressure, can be tolerated without undue physiological dis-

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turbance. The zone of safety at various depths has not been fully determined, but it has been convincingly demonstrated that up to 250 ft., at least, there is ample time for submarine personnel to carry out a chamber escape while breathing air. This work also clearly shows the extreme dangers of the twill-trunk (compartment flooding) method at greater depths even if the compressed air is respirable. The determination of the maximum time tolerated at greater depths is an obvious corollary to this work, as the times allowed for escape from the chamber (Stage II) in this series are far longer than saturated to cause bubble formation and severe damage. It is a surprising finding that chokes (asphyxia due to pulmonary gas embolism) do not occur even after such short exposures to these pressures. Behnke, Thomson & Shaw (1935) found that the period of half saturation of body water and 10 % lipoids was 7 min. only, but that of the remaining 84 % lipoids was about 80 min. A highly technical discussion on the theoretical absorption of nitrogen by the body fluids and fats, and the factors favouring or preventing traumatic bubble formation and air embolism, will serve no purpose

Table 2. *Showing times, in sec., of exposures during various stages of escape procedure*

Goat	Stage I	Stage II	Stage III	Signs
3	120	180	150	None
8	125	175	180	None
6	125	175	180	Severe dyspnoea, multiple râles. Immediate bends in all four legs. Therapeutic recompression ineffective. Killed
3	115	185	120	Bends in hind legs 4 min. later. Died during recompression. Grossly dilated intestines
7	115	185	120	Bend left fore and hind legs. Chokes. Died
6	200	300	180	None
8	200	300	180	None
3	120	300	150	None
15	120	300	150	Transverse myelitis after 10 min. Not improved by recompression. Killed
2	120	300	150	Bend left hind leg. Normal after recompression

All experiments in this table were to a simulated depth of 300 ft. of sea water. Signs of compressed air illness occurred as shown. Stages as in Table 1.

Table 3. *Showing times of exposure, in sec., in six experiments reproducing pressure changes of submarine chamber escape from* 300 *ft. but employing air-oxygen mixtures as shown. No signs of compressed air illness in any experiment*

Goat	Stage I	Stage II	Stage III	Percentage O_2	Equivalent air depth (ft.)	Equivalent O_2 depth (ft.)
8	180	300	150	32·5	250	75
1	180	300	150	34·3	243	81
8	123	420	150	34·2	243	81
1	150	420	150	33·5	246	78
16	150	420	150	33·5	246	78

is actually necessary. The great variation of susceptibility to bends is a constant finding both in high and low pressure work. In this relatively small series there were 60 % fatalities after 3 min. at 300 ft. and yet only 20 % fatalities after 5 min. at the same depth. Risks must be taken in submarine escape but times of almost absolute safety can be determined by further experiments, and, if this method is to be developed, and human experiments commenced, this must be done. With regard to the solution of nitrogen by the fluid and fat of the body, during these short exposures to high tensions of that gas, it would appear that the less accessible areas (brain, spinal cord, fat deposits, joints) are not adequately here. The old adage 'Easy come, easy go' describes the situation just as adequately.

The success of the few 'mixtures' experiments was not surprising as this technique has been extensively developed and used in diving apparatus during the war. However, it is gratifying to see what may be called 'the principle of partial pressures' effective in this particular experiment. The practicability of the use of mixtures in submarine escape is another large problem. On the whole it would mean further complications and elaboration of procedure. It is therefore best that the full limits of air escapes should be defined and exploited before mixtures are considered.

NITROGEN INTOXICATION

Nitrogen intoxication is the second important factor which must be considered in air escapes. Breathing air at such pressures causes marked mental retardation and dulling of the higher faculties. In a number of cases the resultant loss of self-control makes repressed emotions or latent instabilities more manifest. Euphoria, hysterical outbursts, amnesia, loss of judgement and reasoning powers have all been encountered (Admiralty Diving Committee, 1933). High partial pressures of oxygen and carbon dioxide were at one time thought to be responsible for these changes. Behnke *et al.* (1935) first advanced the opinion that the increased tension of nitrogen was the true cause of these disturbances. He has not actually explained the mechanism of this intoxication. This theory has been generally supported and fits the facts better than any other that has been so far advanced. As with alcohol, there is an enormous variation in the effect on different individuals. Unfortunately, nitrogen intoxication is immediate in onset (Shilling & Willgrube, 1937) and persons would be affected even in very short exposures. There is a very close similarity to the effects of breathing fixed percentages of nitrous oxide, where the arterial blood appears to equilibrate at once with the nerve cells; the decisive factor being the tension of the gas breathed, and not the amount that has been absorbed by the whole body.

Method

A number of human subjects were rapidly compressed in air to simulated depths of 220, 250 and 300 ft. of sea water. Reactions to the rapid compression and the increased pressure of air were carefully noted. A simple test was used to estimate powers of concentration and speed of performance. Subjects 'screened' a large series of mixed letters and erased all of one particular letter which occurred with fairly regular frequency. Great emphasis was laid on concentration and accuracy and they were told that, if necessary, speed must be sacrificed to maintain this. The number of letters examined every 30 sec. gave a measure of the speed of performance, and the number of specific letters missed of the accuracy. The test was carried out for 3 min. at surface and continued during compression and at full pressure. It was not practicable during decompression owing to condensation. The element of distraction caused by compression and 'ear clearing' was not considered important as all subjects were trained divers.

Results

Results were extremely varied but a number of findings worthy of note emerged. Some individual results are plotted in Figs. 2–4. Several subjects showed the most marked retardation before arriving at the full depth, especially in the 300 ft. exposures (subjects D and J). Others experienced this during the first minute at full pressure. Many subjects reported dizziness and floating away sensations as

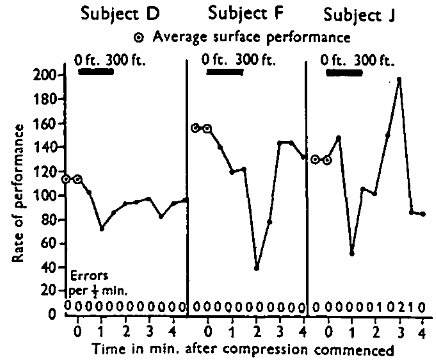

Fig. 2.

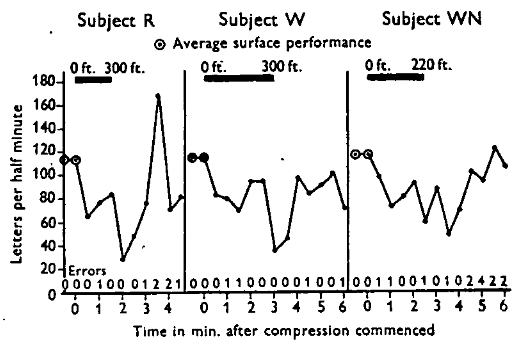

Fig. 3.

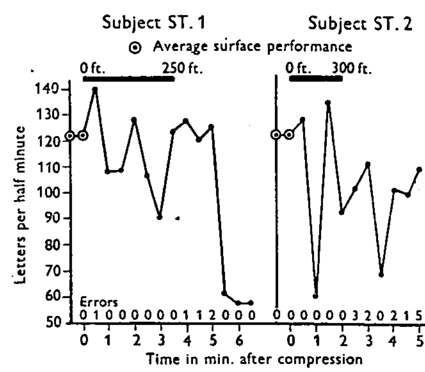

Fig. 4.

they attained the final pressure (Shilling & Willgrube, 1937). Although the intoxication continued, the floating sensations were not experienced while the pressure was constant. It was found that a 'good', experienced, diver appreciated the retardation, and slowed his performance to maintain accuracy. Such subjects were able to increase their speed considerably during the next few minutes (but not to surface speed) and yet remain accurate (see subjects D and F). Other subjects, after slowing, accelerated and lost accuracy. Some continued in this fashion (see subject WN) but others appreciated their deterioration and, by slowing down again, regained their accuracy (see subjects J and R). Some of the subjects were better in their performance at 300 ft. than at 220 and 260 ft. This was probably due to the 300 ft. exposure being the last in the series, with some degree of adaptation and practice. As they expressed it, they were 'getting used to the funny feeling'. This was not always the case, a number being much worse at 300 ft. An instructive example (see subjects ST 1 and ST 2) was a subject whose performance deteriorated, with acceleration, at 250 ft. However, he was able to control himself and return to slow speed without errors. The same occurred at 300 ft. but he was no longer able to maintain control and rapidly deteriorated again, with acceleration.

CONCLUSION AND DISCUSSION

It is realized that these crude tests give little indication of how men would behave in such tensions of air in a real submarine escape. With regard to emotional disturbances during these experiments, the large majority of subjects were mildly euphoric and a few extremely so. The impression gained was that the group reacted as it would to a moderate amount of alcohol, were it acutely administered and its effect uncomplicated by social reactions. No outbursts of any kind were seen in fifty exposures from 220 to 300 ft. It must be remembered that all experimental subjects were divers and knew there was little real danger. The violent episodes previously reported have been in divers underwater at great depth, often in darkness, and in subjects unaccustomed to high pressure work in chambers (*R.N. Diving Report*, 1933; Shilling & Willgrube, 1937; Case & Haldane, 1941). It is quite impossible to imitate real operational stress experimentally. Nevertheless, if escapes from great depths, using air instead of oxygen as a breathing medium, were contemplated, tests of this nature should be carried out on a group of individuals less accustomed to pressure than the trained divers employed in this series. The possibility of emotional outbursts must be admitted but it is also possible that the retardation may be advantageous in a large number of cases. One of the authors has noted that, at these pressures, even experienced workers were inclined to take risks that would appear absurd on the surface, as apprehension was completely lacking.

It has been shown that compression to 300 ft., in times as short as 1 min., does not cause any undue physiological disturbance and that the large majority of subjects were able to concentrate well or moderately well during this period. It has also been confirmed that the nitrogen intoxication is immediate in onset, and, as far as the tests employed show, maximal at this time. The improvement in performance in many cases during the next few minutes is no doubt due to some degree of adaptation. Tests during longer exposures would be of great interest but are not relevant to submarine escape. If air escapes are to be evolved as a practical method, then all submarine personnel should experience high pressures of air on a number of occasions, as is the present practice with divers in training. Severe nitrogen intoxication is an unusual sensation and, even if there were no genuine acclimatization, it should not be first experienced while escaping from a submarine. Finally, it must be emphasized that the submarine escape must be simplified to an absolute minimum and, if possible, no procedure demanding even the smallest degree of skill or judgement should be employed, otherwise success will be jeopardized by not only nitrogen intoxication, but by extreme mental stress.

The main body of experiments described here were carried out at the Admiralty Experimental Diving Unit from June to September 1945, the mixture experiments in March and April 1946.

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