FLUCTUATING ATMOSPHERIC PRESSURES

A NOVEL ENVIRONMENTAL VARIANT OBSERVED IN SUBMARINES

BY

F. P. ELLIS

From the Royal Navy

(RECEIVED FOR PUBLICATION, JUNE, 1948)

The need has been stressed in recent years for relating the design of fighting equipment to the physiological characteristics of the men who must be responsible eventually for its operation, as well as to its mechanical efficiency. Changes in environment may also affect mental or physical performance of a given task or interfere in other ways with physical well-being. The most widely known example is probably that of the airman, who has to contend with rarefied atmospheres, high accelerations, and sudden fluctuations in atmospheric pressure or in the thermal conditions to which he is exposed. The study of aviation medicine and physiology has arisen from the dual needs for designing aviation equipment and aircraft to meet the physical and physiological requirements and limitations of the air crew, and for selecting and training air crew to combat effectively the environmental stresses to which they are exposed.

The changes in environment encountered in submarines are of less violent degree, but in the past, nevertheless, certain avoidable hardships have been accepted as part of the day's work by the submarine sailor, and the need for providing him with an optimal environment is still less generally appreciated than in the case of air crew. The introduction of the "snort" or "schnorkel" to British submarines, to which references were made in both Houses on March 8, 1948, and in the press following the tropical and arctic cruises of H.M. Submarines *Alliance* and *Ambush*, led to a review by the Admiralty of the human factors which are related to the design and operation of modern submarines.

Continuous underwater activity was limited until comparatively recently by the capacity of the batteries to drive the motors which propelled the submarine underwater, and by the ability of the crew to remain efficient in an atmosphere which was steadily depleted of oxygen and to which carbon dioxide was constantly added by the respiratory

processes of the crew. The batteries were charged at intervals by running the diesel engines with the submarine proceeding on the surface, an unhealthy procedure in close proximity to the enemy. The control of the latter factor was achieved during long dives by releasing oxygen when necessary from cylinders or generators, and by removing carbon dioxide with chemical absorbents.

The Netherlands Navy made a considerable advance just before the 1939-45 war when they fitted to their submarines a hollow extensible mast which enabled air for the engines to be conveyed to the submarine whilst it lay submerged, so that the batteries could be charged without obviously disclosing the whereabouts of the submarine. This idea was further developed by the Germans after they captured Dutch submarines in the invasion of Holland, and during the last two years of the war it was incorporated in U-boat design in the form of the "schnorkel," to enable operations to be continued in the face of steadily increasing opposition from Allied air and surface craft equipped with radar. The device proved successful; not only could the batteries be charged in greater safety than previously, but useful underwater speeds were achieved as well. The use of the "schnorkel" in British submarines was investigated in the early years of the war, but the idea was temporarily shelved, and then tried again in 1944.

The German "schnorkel" or British "snort" consists of a hollow mast which can be raised or lowered and connects the interior of a submerged submarine with the ambient air above the surface of the sea. Flooding of the submarine is prevented by a float-operated valve at the upper end of the mast. The mast contains an induction pipe through which air is drawn into the submarine, and an exhaust pipe through which the exhaust gases pass to an outlet a few feet below the inlet to the schnorkel induction, where the gases bubble out below the surface of the sea.

The resistance offered by the long narrow induction pipe to the heavy fresh air requirements of the engines causes a depression of the pressure within the submarine to varying degrees below one atmosphere when the engines are running. The extent of this depression varies in relation to the total revolutions registered by the two main engines, irrespective of whether the engines are being used to charge the batteries, to propel the submarine, or for both purposes. Fluctuations in the internal pressure are related to the state of the sea and swell, which in choppy or rough weather may occlude the air inlet temporarily with water shipped in-board or may close the float valve for short periods during which the engines draw upon the air in the submarine for their requirements; and to the skill of the men and the efficiency of the equipment which maintain the submarine at a constant depth beneath the surface when snorting and so keep the snort inlet above water.

An opportunity for examining the nature of the pressure variations and certain related chemical changes in the atmosphere arose during an early "snorting" cruise in temperate waters in a British submarine which proceeded on the main engines and the snort by day, and at greater depths on the motors with the snort lowered in the hours of darkness.

Pressure Measurements

The tracings shown in fig. 1 were selected from records made during approximately 400 hours snorting with three barographs which furnished 9-inch horizontal tracings of the pressure variations over 7-day, 10-hour, and 2-hour periods respectively. On each "7-day tracing" the corresponding total engine revolutions are indicated, and the average state of the sea and swell for the period under review is shown by the Douglas Scale as estimated through the periscope by the officer of the watch. (See footnote to fig. 1.)

In fig. 3 pressure fluctuations of unusual severity recorded early on in the trial are shown on a tracing from the "2-hour" barograph, and by two tracings from a large barograph which recorded pressure changes over a "10-minute" period.

In order to avoid confusion which might arise from the various terms in use for describing pressures, such as millibars, millimetres of mercury, inches of mercury, or pounds per square inch, the pressure changes are shown here as percentages of one atmosphere, and the aircraft heights at which reduced pressures of similar degree would be experienced are given to facilitate comparison between the two situations.

Chemical Measurements

The partial pressure of oxygen in the air of the submarine was indicated continuously on a Pauling Meter, a direct reading instrument designed in the United States, which depends on the paramagnetic

properties of oxygen as opposed to the diamagnetic properties of most other gases.

When the snort mast was lowered and fresh air ventilation was impractical the percentage of carbon dioxide in the air was measured with an indicator of new design, which depends on the differing thermal conductivities of air samples of different chemical composition. The percentage of carbon dioxide in the air is shown on a galvanometer which indicates the difference in heat loss from two hot wires, one of which is exposed to compartment air saturated with water vapour from which carbon dioxide has been removed by a chemical absorbent, whilst the other is exposed to saturated compartment air from which carbon dioxide has not been removed. The accuracies of these instruments under laboratory conditions correspond reasonably closely with measurements obtained with the Haldane Gas Analysis Apparatus. Each time the instruments were read the atmospheric pressure was noted on a large aneroid barometer which had been calibrated against a mercury column before sailing.

Typical changes in the chemical composition of the air during a 24-hour period on Day 20 are shown in fig. 2. Horizontal lines indicate the partial pressures which correspond to 18 per cent. oxygen and 3 per cent. carbon dioxide at a pressure of one atmosphere, which have been suggested as permissible lower and upper limiting levels for these gases in compartments which must be occupied for prolonged periods.

Traces of carbon monoxide, occasionally caused by back pressure on the underwater exhaust during unexpected submergence with the engines running, or with a following wind from exhaust gases drawn in through the snort induction, were estimated with the Chemical Carbon Monoxide Indicator Mk. III developed at the Royal Aircraft Establishment, Farnborough.

Pressure Changes

The range of the pressure changes experienced on this trial is shown in figures 1A to 1D by records selected from tracings on the "7-day" barograph. Varying degrees of pressure depression below one atmosphere were the main feature when snorting, and when submerged with the snort mast lowered, mild degrees of pressure elevation above one atmosphere were observed due to high pressure air leakages within the submarine.

The marked fluctuations in figs. 1A and 1B were due to slow speeds and low engine revolutions in a choppy sea before the crew were fully accustomed to the controls.

In fig. 1B the relationship between the pressure variations and the total engine revolutions may be observed, and an increase in the amplitude of the fluctuations may be seen when the sea and swell increased on Day 13.

In fig. 1C higher total engine revolutions and faster speeds are related to further depression of the atmospheric pressure to between 85 and 75

FIG. 1.—Variations in the atmospheric pressure within a snorting submarine.

PRESSURE EQUIVALENTS

Percentages of 1 atmosphere ..	70	80	90	100	110	120
Inches of mercury	20.9	23.9	26.9	29.9	32.9	35.9
Millimetres of mercury	532	608	684	760	836	912
Pounds per square inch ..	10.21	11.7	13.1	14.6	16.1	17.5

FIG. 2.—Variations in the atmospheric pressure and oxygen and carbon dioxide content on Day 20.

per cent. of one atmosphere, but the amplitude of the fluctuations is of more moderate degree.

On Day 23 (1D) in a very calm sea the effect of a sudden reduction in total engine revolutions on the pressure depression is shown clearly, and it is seen that in a calm sea pressure fluctuations are observed rarely when the crew are fully accustomed to the controls.

The pattern of the pressure variations is shown in greater detail by enlargement of the time scale in a horizontal direction in figs. 1E to 1L. The vertical scale is much the same, differing only with the calibrations of the three instruments used. Maintained reduction of the atmospheric pressure is observed to be mainly a function of the total engine revolutions, and fluctuations in pressure vary in degree in relation to the state of the sea and the length and height of the swell, the speed of the submarine, and the efficiency of the depth-keeping. Sudden severe pressure fluctuations due to errors of judgment or mechanical faults may occur occasionally, and an example of what may happen is given in fig. 3, to which reference will be made later.

Chemical Changes

In fig. 2 are shown the partial pressures of oxygen and carbon dioxide observed in the air of the submarine during a typical 24-hour period, submerged at a depth of 80 feet by night and proceeding at periscope depth on the main engines using the snort by day.

The partial pressure of oxygen varies with the total atmospheric pressure when the snort is in use, and when communication with the open air is discontinued it may rise with increases in pressure due to such factors as high pressure air leakages within the submarine, or it may fall gradually because of the respiratory requirements of the crew. The latter will be considerably increased if heavy physical exertion is necessary at any time. Physical activity is therefore kept to a minimum when a submarine is submerged for long periods at depths greater than snorting depth in order to conserve the supply of oxygen. The high engine revolutions when snorting on Day 20 were associated with between 20 and 25 per cent. reduction in the partial pressure of oxygen in the air within the submarine.

During the periods submerged with the snort lowered the partial pressure of carbon dioxide

FIG. 3.—Unusually severe pressure fluctuations which gave rise to temporary discomfort in the ears or accessory nasal sinuses at the beginning of the trial.

steadily increased until the fresh air supply through the snort was re-established (chemical absorption of CO_2 carbon dioxide was not carried out). A temporary submergence during the forenoon of this day (see also figs. 1C and G) was associated with a slight further rise of carbon dioxide, and increase of the partial pressure of oxygen to the normal level.

Periods without fresh air ventilation are rarely sufficiently prolonged under peacetime operating conditions to allow the accumulation of harmful amounts of carbon dioxide; and the periodic or continued use of the snort will greatly reduce the probability of undesirably high accumulations occurring in war time.

The Effect on the Crew

In the past the main environmental factors which required control in submerged submarines, which had no air supply from the surface, were progressive depletion of atmospheric oxygen associated with accumulation of carbon dioxide which were the direct results of the respiratory processes of their crews.

Oxygen lack, even when it is mild, is known to be associated at night with diminished visual acuity and an increase in the time required for dark adaptation; and with more severe degrees of anoxia lowered powers of judgment and discrimination, possibly associated with confident unawareness, occur in some people. Thus in the recent war Royal Air Force pilots used oxygen continuously when flying by night, and at altitudes above 10,000 feet by day. The effects of oxygen lack are aggravated by physical exertion, or by any factor which interferes with oxygenation of the tissues such as mild carbon monoxide intoxication.

Carbon dioxide accumulation in the atmosphere will cause headaches, nausea, malaise, and fatigue in some individuals towards the end of long dives (12 to 20 hours) if the facilities for air purification are not available; and these symptoms may be renewed or intensified, or may even occur for the first time after restoration of fresh air supplies on surfacing or on commencing to snort.

No ill effects result from the moderate increases of pressure sustained during submerged periods, provided caution is exercised at the time of opening up to fresh air.

The introduction of the snort has enabled fresh air to be supplied and carbon dioxide to be eliminated whilst submarines are still submerged. This greatly simplifies the problem of air purification under these operating conditions, but it also introduces the new problems of reduced pressures and fluctuating pressures. The effects of these may be subdivided into those due to (1) reduced pressure, (2) sustained pressure fluctuations, and (3) sudden pressure fluctuations.

Reduced Pressures.—The effects of pressure reductions such as those shown in figs. 1F to 1L are simply those of the associated degree of oxygen lack. In fig. 2 it is observed that this would correspond to breathing 16 per cent. oxygen at atmospheric pressure when snorting with high-engine revolutions (640 revs.) or even lower percentages under certain conditions described here. Thus, by night the visual efficiency of men using the periscope whilst snorting might be impaired; and, if careful control was not ensured of the pressures to which the crew were exposed, especially in rough weather, prolonged exposure to an atmosphere poor in oxygen might increase fatigue and impair judgment and general efficiency to an unacceptable degree.

Continuous Pressure Fluctuations.—The pressure fluctuations recorded on Day 7 represent unusually severe conditions which would probably be experienced only if it was necessary to proceed with fairly high engine revolutions at slow speeds in a rough or choppy sea and if the depth-keeping was poor. These conditions did not cause a crew who had grown accustomed to the usual range of pressure changes to complain of immediate discomfort, but the accumulated

effects of exposure throughout the day were thought to induce greater general fatigue than would otherwise have been experienced, and mild anoxia may well have contributed to this. About one third of the crew also complained of headaches, which were generally relieved after snorting finished for the day. It is observed that the pressures were equivalent to spending the day in an aircraft continuously ascending and descending to and from varying heights between 1,000 and 8,000 feet at intervals of a few minutes.

Sudden Pressure Fluctuations.—Pressure fluctuations such as those indicated in figs. 1E to 1L did not cause discomfort or arouse complaints from the crew. More sudden changes, however, such as are depicted in fig. 3, which resulted from temporary loss of control of the depth of the submarine at the beginning of the cruise, added to the general picture given above by inducing temporary symptoms of acute sinus or otitic barotrauma in those individuals who were unable to equalize, with the pressures in the submarine, the pressures within their accessory nasal sinuses or middle ear cavities. This was generally due to temporary blockage of the sinus foramina or eustachian tubes by such factors as mild congestion or catarrhal exudate due to chronic catarrh or acute coryza. Difficulty in clearing the eustachian tubes was generally overcome by men with temporary blockages or unaccustomed to pressure fluctuations, by swallowing, by opening the mouth and retracting the jaw, or by pinching the nose and puffing out the cheeks. Equalizing the pressures was performed automatically by the great majority of individuals after a few days snorting.

Acute dental pain was caused on one occasion when the pulp cavity of a rating's tooth was exposed by extensive caries to sudden pressure changes of fairly severe degree.

The pressure changes shown in fig 3 were experienced before the crew had grown accustomed to fluctuating pressures, and mild symptoms of sinus or otitic barotrauma were experienced by a number of men. The rise of pressure following a sudden reduction was the feature which generally caused discomfort, and with sudden fluctuations of this type it appeared that the rate of change of pressure was of greater importance than the amplitude of the change. Thus the rise of pressure graphically illustrated by tracing "A" caused ratings to complain of unpleasant symptoms, but the more gradual rise shown in tracing "B" did not.

The threshold rate of pressure change at which discomfort was experienced by certain individuals during more severe pressure fluctuations was observed to be of the order of 0.04 to 0.06 inches of mercury per second, although the great majority of healthy men were unaffected once they had become attuned to the more usual type of pressure variation. The changes of pressure related to normal starting or stopping of the engines did not cause discomfort.

In practice pressure changes causing symptoms are experienced infrequently with a trained crew and a carefully handled submarine. Before and after

this cruise the men were examined medically, and also by an ear, nose, and throat specialist who measured their hearing acuity with an audiometer, and from the detailed observations made there is no evidence that such ill effects as may be experienced amount to more than those which persons travelling in aircraft must endure at times. It is necessary to add, however, that after exposure to the unusually severe pressure fluctuations shown in fig. 3 nearly half the crew showed abnormal congestion of their ear drums. These appearances lasted only for a period of hours, or in a few cases for a few days, despite the fact that the men were exposed to pressure fluctuations of considerable, though less severe degree, for most of this time.

One further factor should be mentioned in discussing these pressure changes and the phenomena related to the use of the snort. In certain circumstances—if the engine should be stopped following sudden submergence with the engines running, or when snorting with a following wind—traces of carbon monoxide may be detected in the submarine air. Whilst the degree of this hazard as it has been observed so far would not be harmful alone, the additional anoxia which might result at times in persons already experiencing mild oxygen lack due to low atmospheric pressure would be unacceptable for a prolonged period under operational conditions. Measures for identifying and controlling carbon monoxide are therefore of practical importance.

Conclusion

The environmental factors described here were observed under trial conditions with prototype equipment, and some of the crew were unaccustomed at first to the novel operating conditions. The possible environmental stresses which might affect the efficiency of the crew have been discussed in some detail, but it is emphasized that these are all readily controllable, and the likelihood of undesirable strain being placed on members of a crew will be progressively reduced in future operations by modification of the design of the equipment and control systems, and as a result of operational experience.

In the same way as the aircraft pilot may impose stresses or discomfort on himself or his passengers by steep turns, power dives or other aerobatics, so may the mishandling of a submarine inflict unfavourable environmental conditions on the crew. In war the operational situation will demand at times that unfavourable conditions of varying degree shall be accepted, when the alternative course will involve greater hazards at the hands of the enemy, or when an important attack must be pressed home in special circumstances. The submarine captain, in assessing

the tactical situation, can take full account of any unusual environmental stresses which may be imposed on his crew at these times only if he is well informed of the basic physiological facts and their practical implications, and has at his disposal accurate direct reading instruments for indicating the conditions prevailing within the submarine.

There is no evidence so far to suggest that special conditions will occur in snort-fitted submarines to influence adversely the health or efficiency of the crews, provided that the provision of an optimal environment for the men is borne in mind at all times by those responsible for designing the submarines and for handling them after they are built. On the contrary it is thought that the domestic comfort of the crews will be considerably increased by the reduced motion of the submarine when submerged, by the abolition of the wet and draughty conditions which formerly resulted when a submarine was on the surface in rough weather, and also by the concession allowed the crew of being able to smoke when submerged. It is equally certain that neglect to consider human factors adequately will result in loss of efficiency.

In the Royal Navy when submarines are designed or operations are planned the application of advances in physiology or psychology is ensured by the close co-operation of physiologists, psychologists, and submarine medical officers with the designers of submarine equipment and the operational commands.

The future development of submarines requires that knowledge shall be as complete as possible on the effect of the different environmental variations which may be encountered on judgment and discrimination, visual or auditory functions, efficiency in the performance of psychomotor tasks, or in aggravating fatigue. The effects of prolonged or repeated exposure, or of different combinations of factors, merit special attention. A fascinating field for further practical observations and for fundamental research is thus opened up, and the application of basic knowledge acquired in this way may be expected to extend beyond the particular naval requirement considered here.

This account summarizes the main physiological findings of a preliminary investigation of the effects of "snorting" carried out for the Royal Naval Personnel Research Committee of the Medical Research Council.

I am indebted for invaluable advice to the members and scientific associates of that Committee; and particularly to the Staff of the Royal Naval Physiological Laboratory for advice and assistance before the cruise, and to Mr F. E. E. Smith of the Medical Research Council's Group for Research in Industrial Physiology for preparing Illustrations 1 to 3.