AD/A-003 506

NEON DECOMPRESSION

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Tarrytown Laboratories, Limited

Prepared for:

Office of Naval Research

31 December 1974

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U. S. DEPARTMENT OF COMMERCE

Security Classification

DOCUMENT CONTROL DATA - R & D AD/A-003506

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Union Carbide Corporation, Corporate Research Laboratory, Tarrytown, N.Y. 10591	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

Neon Decompression

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final Report: 1 January 1974 thru 31 December 1974

5. AUTHOR(S) (First name, middle initial, last name)

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6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
31 December 1974	20	0

8a. CONTRACT OR GRANT NO. N00014-74-C-0424	9a. ORIGINATOR'S REPORT NUMBER(S) Technical Memorandum CRL-T-797
b. PROJECT NO. Work Unit NR 201-088	
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

10. DISTRIBUTION STATEMENT

Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY

13. ABSTRACT

During the current contract year this Laboratory has conducted a feasibility program on the applications of neon in mixed-gas diving. The neon source studied was a by-product of the manufacture of atmospheric gases; it is composed of 25% helium, 75% neon, and we refer to it as Neon 75. To develop the decompression tables, we applied modifications of classical theory to existing diving data, mainly experience with helium. The resulting decompression schedules proved to be unexpectedly troublesome in causing sensory problems and delayed effects--whether designed for helium or neon--and satisfactory decompressions could be achieved only if oxygen breathing was included. The planned array of tests over a range of depths and times (150-400 fsw and 30-120 min) was set aside, and efforts were concentrated on producing a dependable table for 250 fsw/60 min. This was accomplished. At least for this depth/time situation, neon appears feasible as a diving gas and seems to be about equivalent to helium in decompression efficiency. Other studies showed divers are comfortable over a broader temperature range in neon, and speech is substantially more intelligible.

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

Security Classification

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Breathing mixtures						
Decompression						
Decompression tables						
Decompression sickness						
Helium speech						
Helium-oxygen						
Neon-oxygen						
Speech intelligibility						
Thermal comfort						

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Security Classification

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ABSTRACT

Hamilton, R.W., Jr. M.R. Powell, D.J. Kenyon and M. Freitag. 1974. Neon decompression. Final report to Office of Naval Research under Contract N00014-74-C-0424. Tarrytown: Union Carbide Corp.

During the current contract year this Laboratory has conducted a feasibility program on the applications of neon in mixed-gas diving. The neon source studied was a by-product of the manufacture of atmospheric gases; it is composed of 25 percent helium, 75 percent neon, and we refer to it as Neon 75. To develop the decompression tables, we applied modifications of classical theory to existing diving data, mainly experience with helium. The resulting decompression schedules proved to be unexpectedly troublesome in causing sensory problems and delayed effects--whether designed for helium or neon--and satisfactory decompressions could be achieved only if oxygen breathing was included. The planned array of tests over a range of depths and times (150-400 fsw and 30-120 min) was set aside, and efforts were concentrated on producing a dependable table for 250 fsw/60 min. This was accomplished. At least for this depth/time situation, neon appears feasible as a diving gas and seems to be about equivalent to helium in decompression efficiency. Other studies showed divers are comfortable over a broader temperature range in neon, and speech is substantially more intelligible.

A. Definition of the problem

The program described in this Final Report has dealt with the possible use of the gas neon for diving. The compelling reason for considering neon is that it can be made available anywhere on earth, free from political restrictions and in unlimited supply. The mixture of neon and helium under consideration here is a product of the industrial fractional distillation of atmospheric air. It is the uncondensed fraction remaining after oxygen, argon and nitrogen have been recovered, and typically consists of 72-78 percent neon and 22-28 percent helium. We call this product "Neon 75."

Physiologically, neon has two properties believed to be distinctly advantageous to divers. It has lower thermal conductivity, and the speed of sound in neon is less than in helium. These properties should result in diminished diver heat loss and decreased voice distortion at depth. These advantages have been felt subjectively by divers, but definitive data has been lacking.

A disadvantage of neon is that it is denser than helium; at pressures beyond 20 atmospheres, it has been shown to restrict the ease of breathing when an inadequate supply is delivered to the diver's breathing equipment. At pressures beyond about 25 atm (800 fsw), the human ventilatory system becomes limiting when breathing neon. This density restriction does not appear to be a problem of depths of less than 600 fsw as long as breathing equipment is adequate.

The additional physiological uncertainty about neon is its effect on decompression. Having solubilities and a solubility ratio (oil/water) similar to helium and a diffusivity resembling that of nitrogen, the decompression results predicted for neon would depend largely on which decompression model is considered and on the time-pressure profile of exposure.

This program was concerned with the development of (1) an alternative to helium from the resource point of view; (2) basic methodology for decompression computation, and with the general physiological properties of the deep diving environment.

B. Half-time development

The initial step in the development of a decompression table is the selection of appropriate half-times. Half-times as used in our analysis are not intended to characterize tissue types but rather are used to represent uptake, by perfusion or diffusion, into various intra- and inter-cellular regions. (In our current practice we refer to "compartments" rather than "tissues" to emphasize the non-physiological aspects of the model.)

Half-times, as used in our treatment, do not imply either diffusion-limited or perfusion-limited loading of regions (both principles are probably involved--it is the one which limits gas transport which is of interest here.) "Half-time," therefore, is an operational term only and is used to describe the time course for the addition of gas to or its subtraction from a given region.

Our experimental work with pigs, performed under a previous contract, indicated that correlations of limb bends and gas loadings could be made only with half-times greater than forty minutes.

Shorter half-times appear to represent areas containing volumetrically large amounts of gas. When this gas was released too rapidly during decompression, numerous bubbles were found to appear in the venous system with a resulting high probability of pulmonary gas embolism. This region described by the shorter half-times appears to be aqueous and perfusion loaded, and therefore similar half-times can be used to describe helium, neon and nitrogen uptake and elimination.

Saturation decompressions indicate that the regions with the longest half-times appear to be diffusion limited. Therefore the longest half-times in our calculations were adjusted to reflect this and to be proportional to diffusion constants (either aqueous or lipid). The fraction 1.7/1.0 was taken as the He/Ne ratio. The longest half-times used were the "classical" helium and nitrogen values as determined by Buhlmann and Workman. These values have been shown by extensive testing to be valid and were therefore considered to be a good starting point. Intermediate half-times were defined such that at the limit of the shortest times equal half-times were used for all gases. The ratios and the half-times selected are given in Tables I and II.

In an analysis of the gas loadings in the pig dives, this system was found to describe successfully the increased gas loadings during mixed gas diving, which could be correlated with limb-bend and pulmonary decompression sickness. An analysis based on gas partitioning by blood perfusion rates and fat/water partition coefficients was not found to be successful. For example, neon-dived subjects were noted to display signs of decompression sickness when

Table I

Ratios of diffusion constants

Gas	Compartment number												
	1	2	3	4	5	6	7	8	9	10	11	12	13
N_2/He	1	1	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2
Ne/He	1	1	1	1	1.02	1.1	1.19	1.28	1.36	1.44	1.53	1.62	1.71

Table II

Half-time values

Chosen on basis of ratios shown in Table I, classical helium saturation and fast-compartment values, and interpolations for intermediate values

Gas	Compartment number												
	1	2	3	4	5	6	7	8	9	10	11	12	13
N_2	5	15	30	50	72	109	140	180	240	272	324	380	480
He	5	15	30	45	60	80	100	120	140	160	180	200	240
Ne	5	15	30	45	61	88	119	153	190	230	276	323	410

gas loadings were lower as computed with fat/water system than helium-dives dubjects which were unaffected by the decompression.

In summary, it can be said:

1. For half-times of less than 30 minutes, there is no difference between gases; thus the gases have the same half-times.

2. For the final compartment, the half-times chosen are based on (i) the ratio of the diffusion coefficients, and (ii) the classical half-time values.

3. For the intermediate compartments, the half-times were based on classical values and combinations of diffusion and perfusion loadings.

C. Matrix development

The half-times defined are used primarily to determine the uptake of inert gases during compression and while at bottom. The constraint matrix is used to determine the rate of upward travel and stop times during the decompression phase of the dive.

In this series of experiments, two matrices were used.

1. Matrix TL-01-M1

This matrix was basically the same as the matrix used in the NOAA OPS experiment conducted in 1973. Certain modifications were made to the NOAA OPS matrix, such as interpolating the M-values to correspond to the half-time values of the TL model. Other inputs to this matrix came from the pig experiments using helium, Neon 75, and a combination of helium, neon and nitrogen as inert gases.

Additional inputs came from the data from other laboratories, such as Duke, EDU, and Bühlmann.

This matrix was used in eight dives.

2. Matrix TL-01-M2

This matrix is an extension of TL-01-M1 to greater depths, and incorporates the results of the earlier dives completed in this series. It also includes some adjustments to remove discontinuities of the matrix. As the NOAA matrix did not extend beyond 250 fsw, the values beyond that point used in this matrix consist of an addition of 10 fsw for every 10 fsw increase in depth. This matrix was used for nine dives. In both matrices, oversaturation tensions, in feet of sea water, depended on the half-time.

D. Table development

The diving tables for this series of experiments calculated from the matrix and half-times were designed to provide continuous breathing of the bottom mixture to the surface. Oxygen was not used initially except for increasing the chamber breathing mixture to 20 percent at either 40 or 60 fsw. Gas elimination was of course slower as there was no "oxygen window" present. Since gas elimination was thus reduced, decompression periods were necessarily longer. For example, the decompression from neon from 120 fsw following a bottom time of 120 minutes required 10 hours 34 minutes. This is to be compared with a similar helium dive (U.S. Navy partial pressure tables) which would use a total decompression time of 127 minutes utilizing 99 minutes of oxygen breathing at 40 fsw. A dive to 250 fsw for 60 minutes would require 182 minutes according to the U.S. Navy diving tables. It is to be emphasized that similar gas loadings in all of the "tissues" were used in these two decompression tables. Despite these extended times, decompression sickness was encountered.

It is noteworthy that essentially no information is available in the diving literature on decompression from short helium dives all the way to the surface without a change to air or oxygen breathing. Since the earliest dives by End and by the U.S. Navy, either oxygen or a shift to air have been used.

E. Experimental diving program

A total of 34 experimental dry chamber man-dives were conducted, using eleven different divers in groups of two. All but one subject made multiple dives; one subject made six dives. All diving subjects were male, ages 20 to 44 years, in good health and at least in fair physical condition.

Before the dives began, an experimental design was prepared which provided exposures at 150, 250 and 400 fsw and for bottom times of 30, 60 and 120 minutes; not all combinations were to be tried.

Using the methods discussed above, a set of half-times and a matrix were assembled and tables were computed. The search for relevant data to use in establishing the M-values revealed a paucity of experience in which divers were decompressed all the way to the surface without a change of gases. We considered this procedure critical to a pure assessment of neon and a realistic comparison of the two gases. The deficiency in data caused a real problem, however, and after only a few dives we were forced to revise the matrix (from TL-01-M1 to TL-01-M2). We attempted to continue with the design, however. After several additional dives, it became apparent that this was not feasible, and the experimental design itself was revised.

We could not justify, using the limited data base available to us, matrix revisions which would clear up the tables. We therefore decided to concentrate on a single type of dive, 250 fsw/60 min. Further, we decided to use oxygen during decompression since it would undoubtedly help and would also make the data base relevant (since oxygen breathing was used on the dives used as our basis set for the development of the matrix).

This change was successful, and all later dives were completed with an acceptable incidence of decompression effects.

Examination of the data reveals the following:

1. Unusual symptoms

There was a remarkably high incidence of decompression sickness other than pain-only limb bends. Mild shock, hearing loss, disorientation, visual disturbances, paresthesia and numbness were seen, while a similar series of dives might well be expected to produce nothing more than limb bends and itching.

2. Residual effects

The symptoms mentioned above seemed to present delayed effects more than would be expected--hours or even days after surfacing.

3. Gases similar

There appears to be no differences in results between helium and neon, with respect to either the nature of the symptoms or their incidence. The neon tables resulted in a slightly shorter decompression time, but this is not statistically significant for the number of exposures involved.

4. Oxygen beneficial

Use of oxygen breathing during decompression reduces substantially the incidence of bends and other symptoms. Oxygen may cause vasoconstriction and may itself participate in bubble formation, but general experience in diving has left no doubt that some oxygen breathing is essential to clear the inert gas from the slowest compartments. Oxygen replaces inert gas, but it appears to exert a beneficial pharmacological effect as well.

The principal task originally posed by the experiments was to assess the feasibility of Neon 75 and other neon mixtures as an alternative to helium for mixed-gas diving. In the limited evaluation of the 250 fsw/60 min decompression situation, we must conclude that neon is at least as suitable as helium. The other ranges tested support this conclusion. The computational methods used here resulted in shorter dives with neon, but for the differences to be meaningful more data are needed.

The question arises of how to assess neon, whether to compare it experimentally with helium in all situations, and if so, how to make the comparison. To use the same criteria but compute for both gases results in different tables, but to use the same table for both gases seems equally inappropriate. The direct comparison with helium is not the issue (since neon might well become quite useful for diving even if it were to take longer in decompression), but it is of great value, because a detailed understanding of the relationship would make it easier to produce tables for neon by extrapolation from helium experience. Future experiments with neon might well be more valuable if the results can be related to helium.

Now that some definite neon decompression experience is available and usable tables have been worked out, it is possible to complete the original experimental design. But to make this matrix more easily and safely usable for deeper, longer dives (e.g., 120 min at 400 fsw), it will be necessary to first establish the limit for the slowest compartments by conducting several saturation dives.

F. Thermal comparison of neon and helium

One important characteristic of neon which may make its use advantageous in comparison with helium (or hydrogen, another alternative) is its lower thermal conductivity, which indicates that neon may cause substantially less heat drain on a cold diver. The critical question here is whether Neon 75 will cause less respiratory heat loss than helium since heat capacity rather than conductivity is probably the controlling factor there. This topic should be the subject of a future study.

Another question of operational importance is that of the thermal comfort zone of Neon 75. We made measurements to attempt to answer this question as part of this neon dive series.

The objective was to use the diver himself as a detector, and let his "comfort" be the criterion we sought in the face of different chamber gas temperatures.

Divers were wired with skin transducers on calf and chest, and mouth temperature was taken periodically with a thermometer. Chamber temperature during the second half hour of the dive was raised and lowered for about ten minutes each, then was adjusted to desires (as nearly as possible) of one of the divers. During the temperature excursions the subjects were queried every two minutes about their preference.

In plots of "preference" vs. temperature, we found that a reasonable correlation could be seen with helium, while with the mixtures rich in neon the two parameters seemed more independent. Preference appeared somewhat less sensitive to neon than helium. Interestingly, the neutral comfort point was about the same--26.5° C--in both gases. It should be noted that the neon mixtures contained appreciable helium--25 percent or more--and that these exposures did not reach the depths where heat loss is known to be a serious problem with helium.

C. Improving speech intelligibility with neon

To the untrained ear, the speech of a diver breathing a helium-oxygen mixture at depths beyond about 300 fsw is virtually unintelligible. Speech of divers breathing mixtures containing neon (e.g., Neon 75) subjectively appears to be more easily understood. If neon is to be properly evaluated as a diving gas, the improvements which it makes in a diver's speech should be quantified. To accomplish this we performed two types of experiments; first, we monitored divers at 680 fsw breathing a Neon 75 mixture, and we set up a special experiment to "titrate" the neon effect at 300 fsw.

1. Neon speech at 680 fsw

During a series of dry chamber dives performed in our laboratory for the purpose of validating decompression tables for 680 fsw using a Neon 75 breathing mixture (5 percent oxygen) (Hamilton and Hedgepeth, The Working Diver 1974, Columbus: Battelle, 1974), speech recordings were made "on the bottom" and at various depths during decompression. Campbell word lists were read in an open chamber (Purisima) filled with the neon mixture, using an Electro-voice 630 table microphone. They were analyzed by Dr. Howard B. Rothman of the Communication Sciences Laboratory at the University of Florida, working under separate ONR funding.

Compared with some comparable helium data, also from Dr. Harry Hollien's laboratory at the University of Florida, recorded at another time, intelligibility was two to three times better (in terms of words correctly identified) with neon than with helium.

2. Neon-helium speech comparison at 300 fsw

The neon mixture of interest to the diving industry is Neon 75, which contains about 75 percent neon. The question arises as to how much neon need be present in a mixture to achieve the beneficial voice properties. A titration experiment was designed to permit the testing of mixtures having 0, 25, 50, 75 and 100 percent of the inert component neon, with the balance helium (and an unavoidable trace of nitrogen).

The depth of 300 fsw was chosen as the shallowest which would show definite intelligibility problems with helium, in order to conserve the expensive gases. Two percent oxygen was chosen, the minimum to provide normal oxygenation at that depth. A standard Kirby-Morgan KMB-8 mask was used for delivering the appropriate gas. It was outfitted with a special microphone (LTV) and duplicate recordings were made using the microphone supplied with the mask; because of problems with the LTV these later recordings were used for analysis. Two dives were made, each with three divers; however, because of helium leakage into the mask and noise in the microphone, data from the first experiment were discarded.

Gases were presented to the divers in a semi-random order; they did not know the composition of the mixture. A five-minute gas wash-in period was used; in all but the first diver's first reading this was given by a supplementary mask. The divers rotated so as to keep one washing in while another was talking.

Because the first experiment had revealed an unacceptably high leakage of helium into the mask, on the second dive the entire chamber was filled with Neon 75. Also, the order of presentation of gases was adjusted to minimize rapid helium buildup in the chamber.

Intelligibility results on the Campbell word lists were determined by Dr. Rothman of the Communication Sciences Laboratory, using 265-269 listeners per diver. Griffith word lists and the Rainbow Passage were also recorded but were not included in this analysis.

The results show that at 300 fsw a diver breathing a neon mixture can enjoy a speech intelligibility of about 75 percent, or nearly 85 percent of his intelligibility under equal conditions but at sea level. The fact that neon makes speech more intelligible at 300 fsw is not surprising, in view of its physical properties and subjective observations. What we did not expect, however, was that only about 50 percent neon in a mixture seems to be necessary to reach near-maximum intelligibility.

We asked the divers for subjective opinions on the best gases for communication, and which was easiest to breathe. Since there was little difference in measured intelligibility, one would not expect subjective opinions to reflect the differences, and they did not.

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