AD 748197

Navy Experimental Diving Unit

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Experimental Diving Unit Report 12-72

THE CALCULATION OF MINIMUM SAFE INSPIRED GAS TEMPERATURE LIMITS FOR DEEP DIVING

by

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July 1972

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Unclassified

Security Classification

DOCUMENT CONTROL DATA - R & D

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

1. ORIGINATING ACTIVITY (Corporate author) Officer in Charge Navy Experimental Diving Unit Washington Navy Yard, Washington, D.C. 20390	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

The Calculation of Minimum Safe Inspired Gas Temperature Limits For Deep Diving

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

Research Report

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

W.R. Braithwaite

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
	14	6

8a. CONTRACT OR GRANT NO 62755N b. PROJECT NO. MF 12.524.014 - 9013DA9K c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) Experimental Diving Unit Report 12-72 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

US Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through Office of Technical Services, Dept. of Commerce, Wash., D.C.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Navy Experimental Diving Unit Washington Navy Yard Washington, D.C. 20390

13. ABSTRACT

Loss of body heat through the lungs of divers breathing cold gas at depths greater than 600 feet can be lethal; no adequate guidelines to safe inspired gas temperatures are currently available.

Review of the recent research in hyperbaric respiratory heat loss has allowed the development of a rational method of calculating the minimum safe inspired gas temperatures for deep diving.

In this report, the recent respiratory heat loss research is summarized, the rationale and calculations of safe breathing gas temperatures are presented, and minimum safe inspired gas temperature limits for depths from 600 to 1000 feet are proposed.

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

Unclassified

Security Classification

Unclassified

Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Diving Cold Tolerance Diving Suits Respiration Deep Submergence						

DD FORM 1 NOV 65 1473 (BACK)

(PAGE 2)

Unclassified

Security Classification

GPO 934-7

ACKNOWLEDGMENTS

The author gratefully acknowledges the advice and support of Dr. Bob Hoke and the most helpful editing of Dr. W. Brandon Wright.

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1. INTRODUCTION

1.1 The Problem

Divers who breathe helium-oxygen mixtures at depths greater than 600 feet in cold water are exposed to severe thermal stress. Even if the diver's skin is kept warm by means of an adequately heated diving suit, by breathing cold gas he can lose more heat through his lungs than his metabolism or the suit can replace. Therefore, to assure the protection of divers in deep, cold water from this potentially life-threatening body heat loss, minimum limits for respiratory gas temperatures are urgently needed.

1.2 Purpose

The purpose of this report is to calculate the minimum safe inspiratory gas temperatures for deep diving and to promulgate this information for use by the U.S. Navy.

1.3 Scope

This report reviews the currently available literature and recent research on respiratory heat loss that is applicable to the estimation of minimum safe respiratory gas temperatures at various diving depths. The rationale and procedures for calculating the proposed respiratory gas temperature limits are explained in detail. Suggested minimum safe inspired gas temperatures for depths from 600 to 1000 feet of sea water are presented.

1.4 Background

Respiratory heat loss (RHL) has been studied extensively since 1945 under various conditions, tropical to arctic, but most studies have been done at one atmosphere pressure. Although Webb and Anis[1] studied respiratory heat loss at 4 atmospheres absolute (4 ata) and 8 ata, the first study which proved that respiratory heat loss would be a limiting factor in deep diving was done in June 1970 at the Navy Experimental Diving Unit by Hoke, Alexander, Jackson, and Flynn.[2] These investigators reported significant problems of two types when divers in a dry, warm chamber at a simulated depth of 25 ata breathed gas at 0-2°C. The first problem was excessive body heat loss in spite of exercise and an ambient temperature of 30°C. This resulted in a rapid drop in body temperature and progressively severe, incapacitating shivering which began in the chest and spread to the limbs and throughout the body. The second problem was acute respiratory distress in one diver who responded to the cold gas with immediate, copious respiratory tract secretions which disabled him and forced him to abort the cold gas breathing and exercise after half an hour. This phenomenon was repeatable in this subject. The studies were repeated at 31 ata with a 7°C inspired gas temperature and similar results were obtained, indicating a cold stress almost as severe as that found at 25 ata with gas 6°C colder.

Hoke, et al. concluded that conditions which allowed a 350 watt or greater respiratory heat loss were hazardous to the diver and that deeper than 19 ata the diver's inspired gas must be heated above 4.2°C. In addition, they felt there would be a direct cold gas effect on the respiratory tract that would place an absolute limit on inspired gas temperatures regardless of respiratory minute volume (RMV) and respiratory heat loss (RHL). As a result of these studies, Flynn and Hoke[4] recommended gas heating requirements for the MK 10-MOD 4 Closed Circuit Mixed Gas Underwater Breathing Apparatus. In addition to a 350 watt limit on respiratory heat loss, they specified a minimum allowable inspired gas temperature as a function of depth, to be met regardless (figure 1).

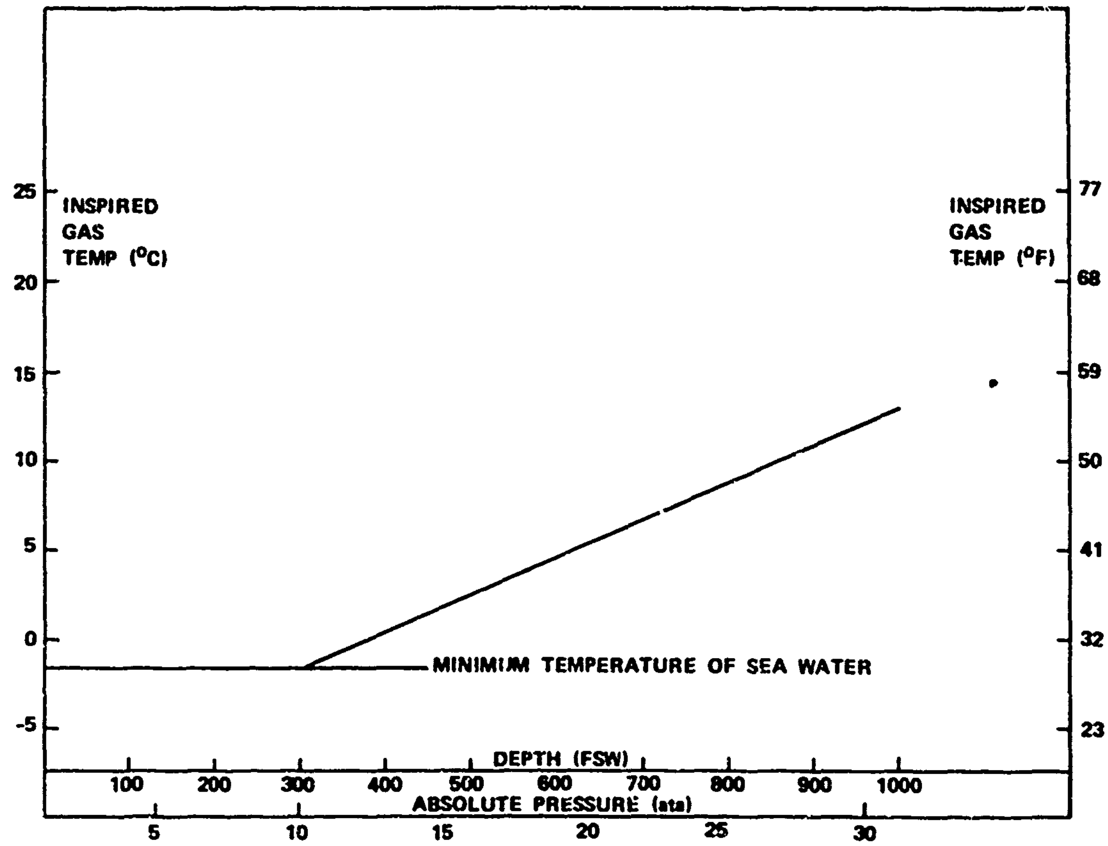

Figure 1. Minimum Allowable Inspired Gas Temperatures at Depth for Mk 10-Mod 4 Closed Circuit Mixed Gas Underwater Breathing Apparatus, from Material Certification Procedures and Criteria Manual for Deep Submergence Systems, NAVSHIPS 0090-028-2010

In May of 1971, a similar study was done by Goodman, Colston, Smith, and Rich[3] at the Westinghouse Electric Corporation facilities under Office of Naval Research (ONR) contract. This study took the research one step further by making measurements on divers immersed in cold water while wearing hot water suits for thermal protection, thereby more closely simulating operational diving conditions. The subjective results were very similar to

Hoke's study; both intense cold and shivering, and copious respiratory tract secretions caused severe diver discomfort and forced termination of dives using 3°C gas at 27 ata.

After considering the computed respiratory heat loss, decreasing core temperatures, and subjective responses in their series of measurements from 15 to 31 ata, Goodman et al. concluded that dives to 27 ata for 90 minutes or more in water 7°C or colder are *hazardous*, and dives to 21 ata for 90 minutes or more in water 2°C or colder are liable to be discomforting to the point of distraction and task performance degradation.

1.5 Current Limits

The current limits, as found in the Material Certification Procedures and Criteria Manual for Deep Submergence Systems[6], are defined by the Minimum Allowable Inspired Gas Temperature vs. Depth line shown in figure 1, with the additional restriction to limit respiratory heat loss to 350 watts or less. These limits were tentative recommendations made by Flynn and Hoke[4] before their data had been carefully analyzed and prepared for publication. The analysis of available experimental data presented in this report will show the need for modification of these limits.

2. PROCEDURE

2.1 General

As explained in Appendix A, respiratory heat loss (RHL) at depth is directly proportional to the respiratory minute volume (RMV), the gas density (ρ), the specific heat of the gas (Cp), and the change in temperature it undergoes (ΔT). These relationships, summarized by the formula: $RHL \propto RMV \bullet \rho \bullet Cp \bullet \Delta T$, were used in the mathematical calculation of the minimum breathing gas temperature curves according to the methods outlined in Appendix B. The basis for these calculations was established by the similar recommendations of the two recent groups of workers in the field of hyperbaric respiratory heat loss, Hoke et al[2] and Goodman et al[3]. Their definitions of hazardous and detrimental diving conditions were used as a starting point from which to mathematically project temperature vs. depth curves. Although the two studies contain similar recommendations, they produced very different temperature vs. depth curves. Comparative analysis was undertaken to understand the cause of this difference.

2.2 Analysis

The basic analysis was performed by graphical comparison of the data from these two studies with mathematical reanalysis where necessary to resolve the inconsistencies.

First, a plot of watts RHL vs. depth was made from Goodman's data for 2°C and 7°C at a RMV of 40 lpm. The 2°C point corresponding to the hazardous condition of 7°C gas at 27 ata (for 325 watts RHL) was found to be about 24 ata. Likewise, the 7°C point corresponding to the detrimental condition of 2°C gas at 21 ata (for 270 watts RHL) was found at about 23 ata. These four points were then used to plot Goodman's detrimental and hazardous lines on a temperature vs. depth plot in figure 2. These lines were extended, by the method outlined in Appendix B, from 600 to 1000 feet using Goodman's regression formula for expired gas temperature as a function of inspired gas temperature: $y = .649 x + 22$. Hoke's 350 watt line, from the text of reference 2, and his minimum allowable inspired gas temperature line from reference 6, which corresponds roughly to 300 watts RHL, were also plotted for comparison.

It was then determined that the only significant difference between the two projections was due to the different methods of estimating expired gas temperatures. An inspired vs. expired gas temperature plot was made for each depth to elicit the differences in assumptions about these important variables. In both cases there was little effect of depth,

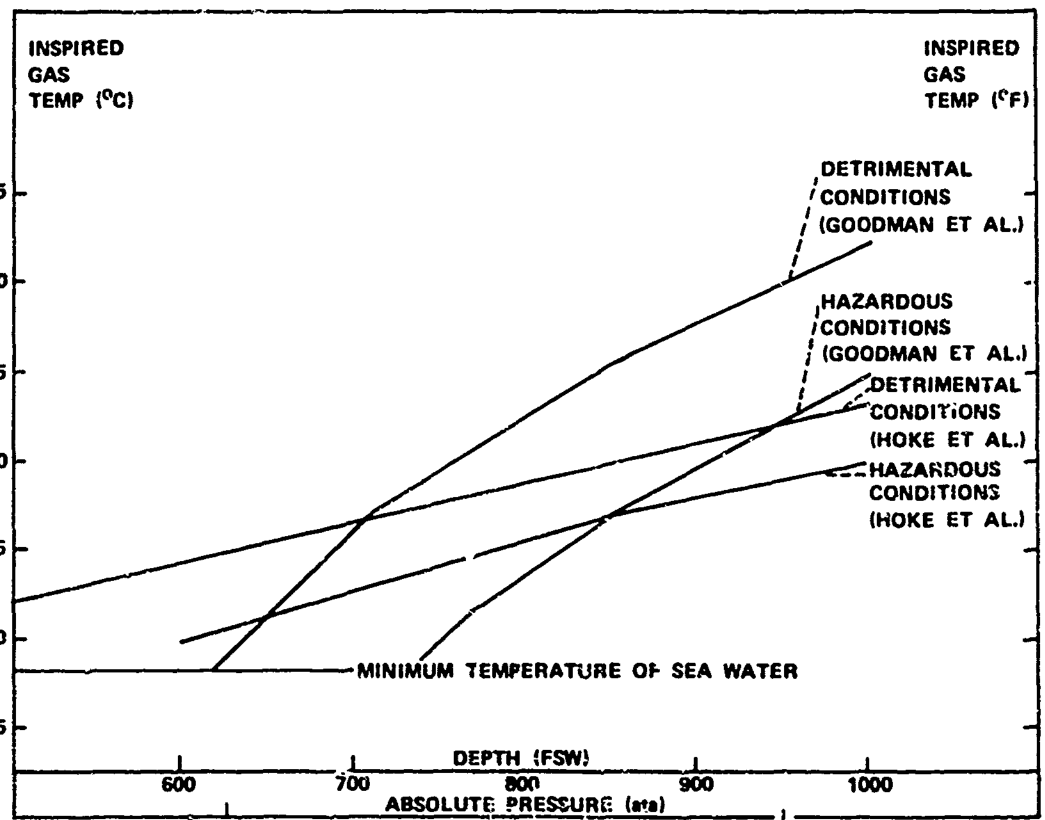

Figure 2. Inspired Gas Temperatures at Depth Resulting in Respiratory Heat Loss Causing Detrimental and Hazardous Conditions, from calculations by Hoke et al[2] and Goodman et al[3]

but Goodman's regression of expired gas temperature as a function of inspired gas temperature was remarkably different than Hoke's assumption of a constant 30°C expired gas temperature. A third line published in 1955 by Webb[5], who studied respiratory heat loss in arctic air, provided another contrast. The difference between Goodman's regression line and his plot of inspired vs. expired gas temperatures suggested that an error had been made in his calculations. Therefore, a regression analysis was performed on Goodman's published raw data and on Hoke's raw data of inspired and expired gas temperatures using a least squares fit program on a Wang 370 programmable calculator.

The results of this analysis are plotted in figure 3. Hoke's data produce a slightly curved line which is essentially identical to that found by Webb:

$$y = .004\,x^2 + .09\,x + 29.3$$

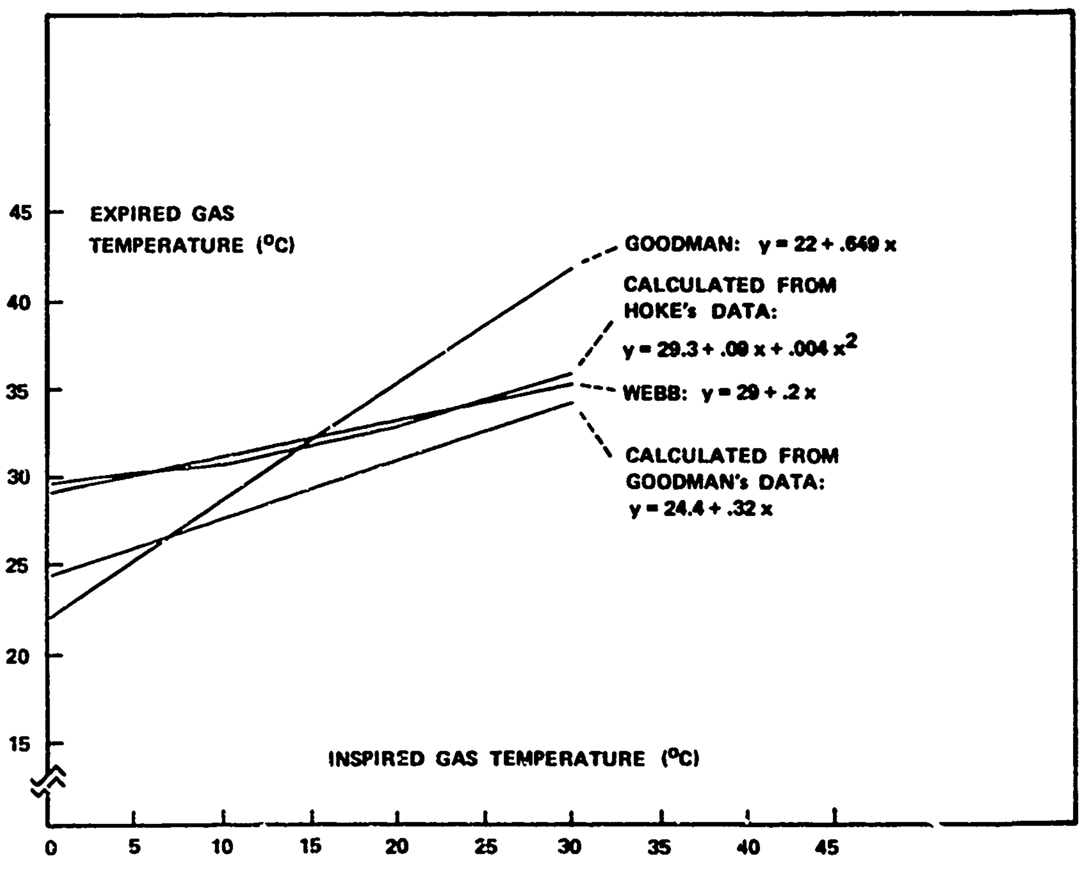

Figure 3. Regression Lines of Expired Gas Temperature as a Function of Inspired Gas Temperature

Goodman's data produce a straight line which is offset but almost parallel to Hoke's line:

$$y = .32\,x + 24.4$$

This offset can be attributed to differences in experimental design or measuring devices and techniques. Since Goodman's data were obtained under conditions more closely simulating the working diver, the regression formula from his data was used to make mathematical extensions of the detrimental and hazardous conditions. However, when plotted as a temperature vs. depth curve, the lines extended using either derived formula are almost identical.

In an attempt to define the effect of Respiratory Minute Volume (RMV) quantitatively, Goodman's data for the drops in rectal and calculated body temperatures were plotted against RMV for each depth. Although there was a great deal of scatter of the data points, the general trend was a greater drop in temperature with greater RMV. A significant change in slope with depth could not be defined graphically because there were only three points at each depth and temperature combination (except at 27 ata with 2°C gas) and the data scatter was too great. Since we know that body temperature rises with exercise at surface pressures, there must be some depth at which this trend is reversed, but that depth could not be found in these data.

Finally, the detrimental and hazardous points were extended mathematically (as outlined in Appendix B) from 600 to 1000 feet using the regression formula for expired vs. inspired gas temperatures derived from Goodman's data. These are presented in figure 4.

3. DISCUSSION

3.1 RMV Effect

One of the most important variables to discuss is the effect of the diver's ventilation rate or RMV. Since respiratory heat loss (RHL) is directly proportional to RMV, the assumption follows that if a diver breathes twice as much cold gas, he will be in a more hazardous diving situation. However, the situation is not that simple. The heat balance of the body depends on the heat produced by metabolism as well as that lost by the various routes. Physiologically, RMV varies directly with the rate of metabolism. Therefore, the RMV is approximately proportional to the heat produced by that metabolism. Since RHL is proportional to RMV, then RHL and metabolic heat production are also proportional. The metabolic heat production is independent of ambient pressure and RHL is proportional to absolute ambient pressure (Appendix A), so the amount of heat lost by a diver at a given level of exercise will change with depth, whereas the amount of heat produced will not.

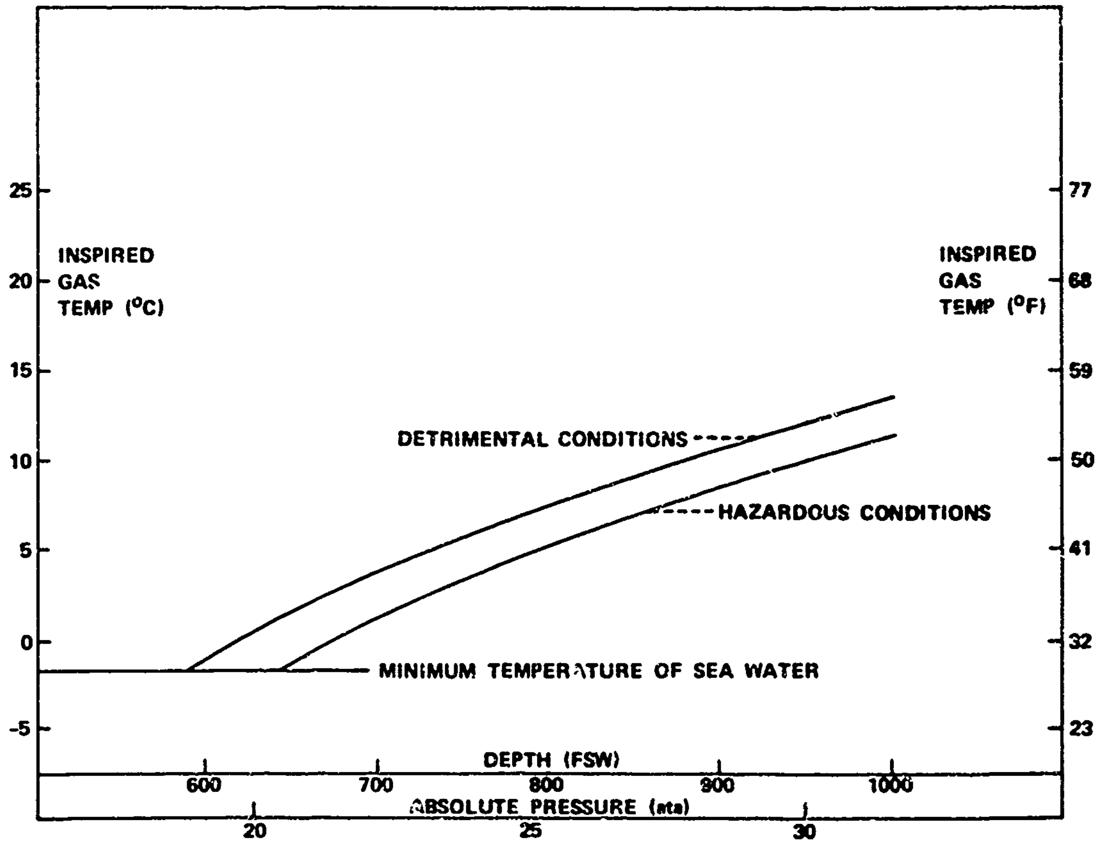

Figure 4. Inspired Gas Temperatures at Depth Resulting in Respiratory Heat Loss Causing Detrimental and Hazardous Diving Conditions, as calculated from experimental data of Goodman et al[3]

In the two studies under consideration, two trends were seen. Exercise on the surface produced increases in body temperature, indicating that more heat was being produced than lost. At the deeper depths, however, the opposite was true, indicating that more heat was being lost in the increased respiratory minute volume than was being produced by the increase in metabolic rate. These trends of body temperature, and hence body heat balance, were seen to switch at between 13 and 19 ata when divers were breathing 2°C gas[4]. This means that at some depth between 400 and 600 feet of sea water the net effect of exercise rate on body heat balance was zero. Thus, both the amount and the direction of the effect of RMV on body heat balance are dependent on the absolute ambient pressure.

Fortunately, at the depths of current operational diving the effects of RMV on body heat balance are relatively small because the two opposing effects of exercise on body heat balance, increased RMV and increased metabolic heat generation, are approximately equal. Therefore, RMV can be neglected as a significant variable for the purposes of the proposed breathing gas temperature limits. However, as one goes deeper than 1000 feet, the cooling effects of increased RMV will increase sharply and must be anticipated.

It is, of course, not possible to limit a diver's breathing rate to meet some arbitrary figure since RMV is controlled involuntarily by the diver's metabolic rate. Therefore, in operational diving, the use of RMV limits to control respiratory heat loss is completely impractical. Thus, this elimination of RMV as a variable in respiratory heat loss estimation has definite practical advantag·

3.2 Countercurrent Effect

The phenomenon described by the inspired vs. expired gas temperature curves is that of the respiratory tract countercurrent heat exchanger. As cold gas enters the respiratory tract, it absorbs heat from the tissues encountered until it is finally raised to body temperature (37°C) in the alveoli. However, as Goodman points out, it is not correct to assume that the gas leaves the body at this temperature since heat is transferred back to the respiratory tract as the warm gas exits over previously cooled tissues. Likewise, it is not valid to assume any constant expiratory gas temperature since the temperature of the inspired gas is one of the factors which determines the amount of heat transferred (from expired to inspired gas) by this anatomic heat exchanger. As inspired gas temperatures get colder, the respiratory tract tissues will lose more heat in warming the gas to body temperature during inspiration, and then will absorb more heat during expiration, thus becoming more efficient as a heat exchanger. This effectively reduces expired gas temperature and moderates the respiratory heat loss as a function of inspired gas temperature.

As one goes deeper and gas density increases, the heat capacity of a given volume of gas increases. Since the heat capacity of the respiratory tissues remains constant, th. efficiency of the countercurrent heat exchanger is reduced. Although it could not be demonstrated in these data, this should cause the expired gas temperature to be warmer than predicted and respiratory heat loss to be increased over that expected at deeper depths. Great care must be used in mathematically extending these experimentally determined points to greater depths, since a very small difference in the expired gas temperature can have a great effect on respiratory heat loss, and the effects of depth described above have not been measured.

3.3 Hypersecretion Syndrome

The effect of cold gas on the respiratory membranes causing the copious secretions seemed to be more constant and less individually variable in Goodman's study than in Hoke's. This reaction is depth and temperature dependent but appears to be more complex than a simple, direct response to cold gas. More research is urgently needed to uncover the pathophysiology of this diving condition. However, since the hypersecretion syndrome occurred at depth and temperature combinations deeper and colder than the proposed limits, hypersecretion effects are not expected to occur within them.

3.4 Proposed Respiratory Gas Temperature Limits

Although all the above factors have been considered, the proposed limits deal only with the two variables with large, known effects, the inspired gas temperature and the depth. The limits, shown in figure 5, are based upon the points defining detrimental and hazardous diving conditions established experimentally by the two groups of workers. The mathematical projection of these points to depth/temperature limits was based on the known dependence of RHL on absolute pressure and on the observed relationships of inspired and expired gas temperatures at these depths.

Of course, total heat loss is also dependent on the time a diver spends in negative heat balance. The proposed limits have been selected such that a diver who spends even a short time deeper and colder than this minimum safe inspired gas temperature curve may experience a potentially lethal diving condition from both the hypersecretion syndrome and excessively rapid body heat loss. Separate curves at warmer gas temperatures for specific exposure times are not included in the proposed limits simply because not enough data is available to support this extension. For these reasons divers should be monitored closely when approaching these limits to establish a time limit on the dive if necessary and to assure that the temperature/depth limits are not violated.

This proposed limit curve correlates exactly with the currently used limits at 1000 feet but falls off much more rapidly with decreasing depth and allows 300 feet more diving depth without the need to heat the diver's gas at minimum water temperature. In addition, the maximum RHL limitation has been avoided. Comparison with Goodman's calculations is also favorable but not helpful since they were apparently made with a different temperature regression formula. These limits do, however, correlate well with Goodman's subjective observations and conclusions.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusion

Careful comparison of the two recent studies of the effects of cold gas breathing on divers has enabled resolution of some of their apparent differences so that limits for minimum safe inspired gas temperatures for use in deep diving could be proposed with confidence.

4.2 Recommendations

It is recommended that the temperature/depth line, figure 5, be established as the limit for minimum safe inspired gas temperatures for use in operational dive planning and underwater breathing apparatus certification in the U.S. Navy.

DEPTH FSW	TEMPERATURE °C	°F
600	-1.0	30.1
650	1.7	35.0
700	4.0	39.2
750	6.0	42.9
800	7.8	46.1
850	9.4	48.9
900	10.8	51.5
950	12.1	53.8
1000	13.3	55.9

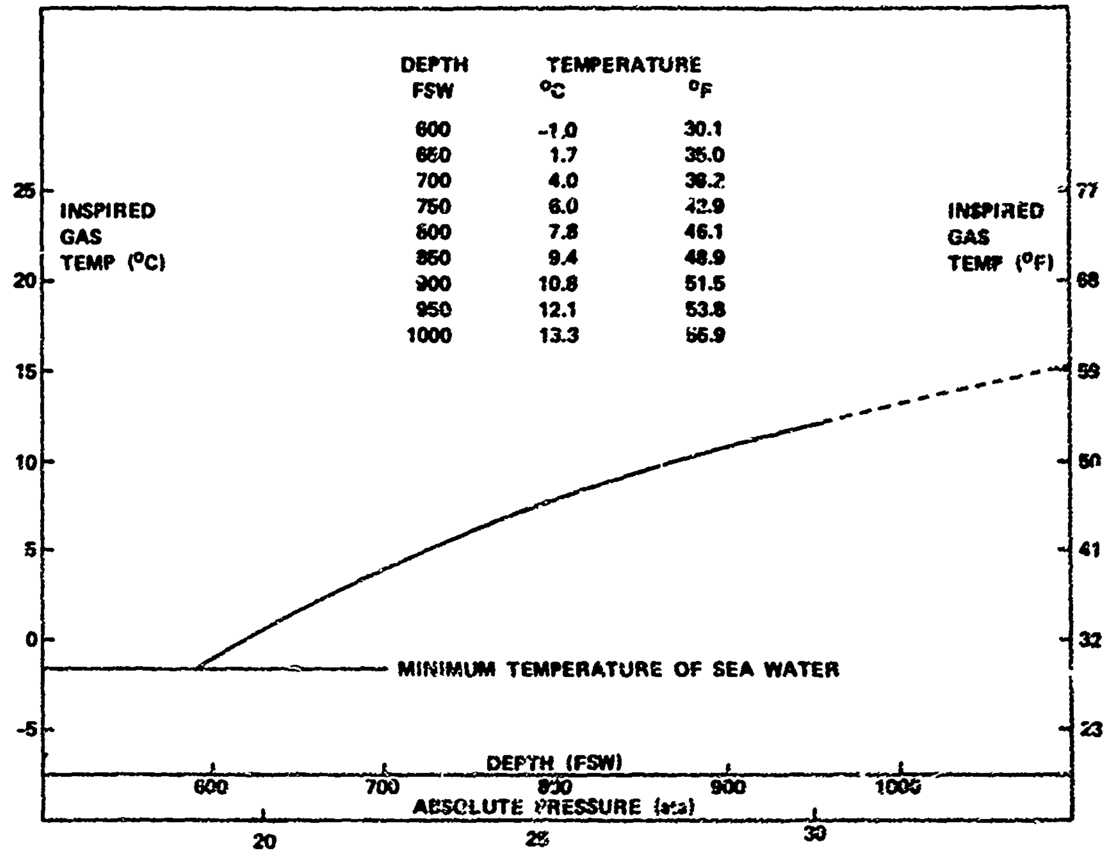

Figure 5. Minimum Safe Inspired Gas Temperature Limits

This limit specifies the *minimum* temperature for breathing gas being delivered to a diver at each depth and assumes that all other measures to keep the diver warm (i.e. hot water suit) are being taken. The level of respiratory heat loss at these depths and temperatures is thought to be tolerable with some degree of safety, however, it must be pointed out that temperatures only 2 and 3 degrees Celsius colder are considered *hazardous.* Even at the minimum temperatures, it has been shown that exposures have been discomforting to the point of distraction and task performance degradation, so that these must truly be considered *minimum* temperatures from a safety standpoint, regardless of the bottom time, work rate, or other factors.

When using a system which does not heat the breathing gas, we can assume that the gas will be at ambient water temperature and the minimum safe inspired gas temperature curve sets a limit on diving depth in a given temperature water. When using or designing underwater breathing apparatus, the curve specifies the minimum temperature to which the gas must be heated at depth to lessen the hazard of this obligatory respiratory heat loss. Of course, inspired gas temperatures higher than the minimum are desirable whenever possible to increase the safety and comfort of the divers.

For diver safety, underwater breathing apparatus selected for dives deeper than 600 feet should have continuous inspired gas temperature monitoring and verbal communications. In addition, diver core temperature monitoring will be helpful when it becomes operationally feasible.

The need for proven, efficient, respiratory gas heating devices and temperature monitors for deep diving equipment is apparent.

In addition, because of the obvious impact of this limitation on deep diving, more research is needed in hyperbaric respiratory heat loss to resolve the unknowns such as the relative effects of RMV and exercise, the effects of depth on the respiratory countercurrent heat exchange mechanism, the pathophysiology of the hypersecretion syndrome, and probably most important of all, the safe time limitations at certain depths and temperatures.

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Appendix A

Body Heat Balance

The factors involved in the heat balance of the body should be covered briefly to facilitate the discussion. Body heat is generated by metabolism and can be calculated from known oxygen consumption and work output. This heat is then lost either through the skin or through the respiratory system, but can be buffered to some degree by the body's heat storage capacity.

In the case of the submerged diver wearing thermal protection, the loss of heat through the skin is reduced to loss by conduction to the thermal protection material, and the factors of radiation and evaporative loss are assumed to be zero. It is noted that in the Goodman study, use of a Diving Unlimited MK XAD free flooding hot water suit with 2 gallons per minute of 110°F water flow maintained skin temperature at only 92°F and therefore lessened but did not eliminate or reverse heat loss through the skin as some might expect. The amount of heat lost in this manner is dependent on the temperature gradient between body core and skin covering, the thermal conductivity of the intervening tissues, and the body surface area.

In calculating heat lost from the respiratory system, heat loss due to heating and humidification of the breathing gas must be considered. The latent heat of vaporization lost to the water used to humidify the inspired gas does not change significantly with depth and diminishes to an insignificant fraction of total respiratory heat loss (RHL) at the depths of interest. Therefore, RHL at depth can be estimated to be the heat necessary to raise the gas from inspired temperature to expired temperature. This respiratory heat loss is directly proportional to the respiratory minute volume, the gas density, the specific heat of the gas, and the change in temperature it undergoes.

This relationship is described by the formula:

$$RHL \propto RMV \bullet \rho \bullet Cp \bullet \Delta T$$

where

RHL = The respiratory heat loss.

RMV = The respiratory minute volume. The amount of heat lost is proportional to the amount of gas breathed so that if respiratory minute volume is doubled (e.g. from 20 lpm to 40 lpm) then the RHL will also be doubled.

ρ = The density of the gas. This is proportional to the absolute pressure or depth so that as the diver goes deeper the amount of heat absorbed by a given volume of gas undergoing a given temperature change will change in proportion to the absolute pressure.

Cp = The specific heat of the gas. This changes somewhat during the dive according to the changes in relative amounts of the fractional gas components (e.g. He, O_2, N_2, CO_2, and H_2O vapor). These changes, however, are very small and specific heat of the gas can be considered constant and equal to that of the major inert gas in the mixture.

ΔT = The difference between inspired and expired gas temperature (Te-Ti). This value is extremely sensitive to small changes and varies with inspired gas temperature.

Appendix B

Mathematical Techniques

Regression analysis of expired gas temperature as a function of inspired gas temperature was performed using a least square fit program on a Wang 370 programmable calculator.

Mathematical extention of inspired gas temperature vs. depth lines from data points or lines was accomplished using a regression formula for expired vs. inspired gas temperature and ratios of absolute depths in the following way:

If the regression of expired gas temperature (Te) on inspired gas temperature (Ti) is known and assumed to be linear:

$$Te = a \bullet Ti + b$$

then the gas temperature change (ΔT) is known for a specific inspired gas temperature (Ti):

$$\Delta T = Te - Ti = b + (a - 1) \bullet Ti$$

In the RHL equation from Appendix A: RHL $\propto$ RMV $\bullet \rho \bullet$ Cp $\bullet \Delta T$, when RMV is held constant (and gas specific heat is known to be constant), RHL is only proportional to gas density and gas temperature change: RHL $\propto \rho \bullet \Delta T$ and, since gas density is proportional to absolute pressure (P), a constant RHL will result if ΔT is inversely proportional to absolute pressure: $\Delta T \propto 1/P$.

Therefore, a ΔT can be calculated for each depth which will result in the same RHL at a specific RMV:

$$\Delta T_1 = \frac{\Delta T_0 P_0}{P_1}$$

and then the inspired gas temperature can be calculated for each depth:

$$Ti = \frac{b - \Delta T}{1 - a}$$

When plotted against depth, these inspired gas temperatures define the conditions along which RHL is constant for a given RMV, and this is used to extend a safe minimum point into a minimum safe inspired gas temperature vs. depth curve.