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NAVY EXPERIMENTAL DIVING UNIT
REPORT NO. 10-80

RESPIRATORY HEAT LOSS LIMITS IN HELIUM-OXYGEN SATURATION DIVING

June 1980

By

C. A. PIANTADOSI

NAVY EXPERIMENTAL DIVING UNIT

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DEPARTMENT OF THE NAVY
NAVY EXPERIMENTAL DIVING UNIT
Panama City, Florida 32407

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Convective respiratory heat transfer in divers breathing cold helium-oxygen is a major avenue of body heat loss for which there is no effective thermoregulatory compensation. Review of recent studies of hyperbaric respiratory heat loss provides a physiological data base for updating current minimum inspired gas temperatures for saturation diving. The new proposed inspired gas temperature-depth curve is based upon a maximum convective respiratory heat loss of 20 $W.m^{-2}$ for a resting diver maintaining thermo-

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neutral skin temperature in a hot water suit. This level of respiratory heat loss is predicted to allow an average rectal temperature drop of 0.25°C per hour, and will support a four hour mission. The new limits are designed to allow divers with any ventilatory response to exercise or cold to gain heat from exercise, although it is expected that most of the exercise heat remaining after obligatory increases in respiratory heat loss from the ventilatory response to the exercise, will be dissipated through the diver's skin as he adjusts his hot water flow and temperature for comfort.

ABSTRACT

Convective respiratory heat transfer in divers breathing cold helium-oxygen is a major avenue of body heat loss for which there is no effective thermoregulatory compensation. Review of recent studies of hyperbaric respiratory heat loss provides a physiological data base for updating current minimum inspired gas temperatures for saturation diving. The new proposed inspired gas temperature-depth curve is based upon a maximum convective respiratory heat loss of 20 W/~~m~~ sq m for a resting diver maintaining thermoneutral skin temperature in a hot water suit. This level of respiratory heat loss is predicted to allow an average rectal temperature drop of 0.25°C per hour, and will support a four hour mission. The new limits are designed to allow divers with any ventilatory response to exercise or cold to gain heat from exercise, although it is expected that most of the exercise heat remaining after obligatory increases in respiratory heat loss from the ventilatory response to the exercise, will be dissipated through the diver's skin as he adjusts his hot water flow and temperature for comfort.

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Introduction

The high thermal conductivity and heat capacity of hyperbaric helium-oxygen breathing mixtures increase convective respiratory heat transfer to levels which produce major thermal balance problems in cold water saturation diving below 600 FSW (12). On the basis of early respiratory heat loss studies by Webb and Annis (14) in divers immersed in cold water at 200 FSW, Tauber et al. (10) made a theoretical prediction that respiratory heat loss would exceed metabolic heat production at 850 FSW and 4.2°C water temperature. This prediction was subsequently verified in exercising divers immeresed in 1.7°C water at depths to 850 FSW (3), and in exercising men breathing cold helium-oxygen in a dry chamber at depths between 200 and 1000 FSW (4). Both groups of investigators reported copious upper respiratory tract secretions associated with cold gas breathing, and found that respiratory heat loss rates of 325 to 350 watts were detrimental or hazardous to thermal balance in divers performing moderate work ($\dot{V}_E$=40 $1.min^{-1}$). In an analysis of the results of these two studies, Braithwaite calculated a minimum safe inspired gas temperature versus depth curve for the U.S. Navy by extrapolation of the above hazardous conditions to depths between the surface and 1000 FSW (2). Braithwaite's method assumed that increases in heat production with exercise would be offset by increases in respiratory heat loss from the ventilatory response accompanying the exercise, and the diver would remain in thermal balance.

Recently, the Navy Experimental Diving Unit investigated the ventilatory response to cold helium-oxygen exposure in divers (6), and found that respiratory heat loss is not well compensated by increased heat production, and the fraction of metabolic heat production available to maintain body core temperature depends upon the $\dot{V}_E/\dot{V}_{O_2}$ ratio, which is highly variable among divers of different body types. The inadequate thermal response to respiratory heat loss was confirmed during a subsequent study of the effects of cold helium-oxygen breathing on rectal temperature and metabolic heat production of four resting divers at depths between 640 and 1800 FSW while maintaining comfortable mean skin temperatures and using a single cold inspired gas temperature (7). The results of these studies and the operational experience both in the open sea and at the Navy Experimental Diving Unit using Braithwaite's curve indicate the need for a new approach to the calculation of safe minimum inspired helium-oxygen temperatures. This report presents the basic physiological data and concepts necessary to calculate safe inspired gas temperatures for four hour saturation excursions, and generates revised minimum inspired gas temperatures for depths between 200 and 1500 FSW.

Methods

The thermal physiological data which forms the basis for this report was obtained during three helium-oxygen saturation dives conducted by the Navy Experimental Diving Unit in 1979. These dives included the 1000 FSW TDCS dive, the 650 FSW MK 11 UBA dive, and the 1800 FSW Deep Dive '79. Fourteen of eighteen male subjects participated in the thermal experiments. Their mean age was 32 $\pm$ 4 years, height 181 $\pm$ 7 cm, weight 83.6 $\pm$ 9.0 kg, and DuBois surface area 2.05 $\pm$ .13 m^2. All subjects were well conditioned, and none had significant cold water diving exposures for several months prior to their respective dives.

During the dives, the oxygen partial pressure was automatically maintained between 0.35 and 0.40 ATA, except during the 1800 FSW dive where it was maintained between 0.40 and 0.45 ATA. The physical properties of the breathing gases used in these studies are summarized in Table 1. Chamber carbon dioxide was usually between 2 and 4 mmHg. Ambient chamber temperature was kept at a level comfortable to the occupants, increasing from 29 to 32°C as depth increased between 640 and 1800 FSW. Relative humidity was maintained at 40-60% and verified by comparison of wet and dry bulb temperatures obtained during the studies.

The thermal experiments were performed dry and were of two types. The first experiments included 8 exposures of 4 bathing suit clad subjects to 20°C helium-oxygen at 640 FSW for 60-120 min at rest, followed by a repeat study by the same 4 subjects with continuous leg exercise at 50 watts. Six additional resting subjects were exposed to 15°C helium-oxygen at the same depth for 60-120 min. The second type of study consisted of 16 cold helium-oxygen breathing experiments of 60 min duration by four subjects at 640, 1000, 1400, and 1800 FSW using a single inspired gas temperature. During the studies, measurements were made of mean skin temperature ($\bar{T}_{sk}$), rectal temperature (T_{re}), convective heat flow (C_{sk}), radiant energy loss (R), respiratory heat loss (RHL), and metabolic heat production (M). Methodological techniques have been described in detail in the reports which provide the data base for this analysis (6, 7). More complete discussion of the thermal balance equations critical to this report can be found in the Appendix.

Results

In determining the effect of respiratory heat loss on thermal balance, an estimate for each term in the basic heat balance equation developed in the Appendix is required. For a diver in a hot water garment, this equation is:

$$S = M - (C_{sk} + RHL) \qquad \text{(eq. 1)}$$

where S is the loss (or gain) in body heat content determined from the difference between skin heat loss (C_{sk}) plus respiratory heat loss (RHL) and metabolic heat production (M). If C_{sk} plus RHL is greater than M, S will be negative, the diver will have a net heat loss, and his core temperature will decline. The relationship between S calculated from equation (1) and change in rectal temperature for resting divers losing large quantities of respiratory heat with normal levels of skin heat loss and constant skin temperature is shown in Figure 1. The linear relationship between S and ΔT_{re} is excellent, enabling us to predict S from a known change in rectal temperature. According to current U.S. Navy guidelines (15), decreases in T_{re} in divers are expected, but should not exceed 1.0°C over the duration of a dive. Since the relationship between S and T_{re} is linear, a rate of rectal temperature change of 0.25°C per hour will permit a 4 hour mission. Figure 1 shows that a decrease in S of 12 $kcal.m^{-2}\ hr^{-1}$ (14 $W.m^{-2}$) will result in a ΔT_{re} of 0.25°C per hour in a resting diver.

Having established 14 $W.m^{-2}$ as the maximum decrease in body heat content for resting divers with high RHL rates, it is necessary to estimate the ability of the body to compensate for RHL by increasing heat production at skin temperatures maintained by divers in hot water garments. Measuring skin heat loss in a resting diver in a free flooding hot water suit is complicated by variables such as body surface area, amount of adipose tissue, skin to hot water temperature gradient, effect of the neoprene liner, and non-uniformity of hot water distribution. Early studies showed that maximum local skin temperatures should not exceed 43.3°C (110°F) for long periods because of pain and burns (5, 9). In very cold water, with inlet hot water temperature adjusted to 43°C, $\bar{T}_{sk}$ has been found to be about 33°C (92°F) for divers wearing Mark 16 hot water suits (3). Part of the explanation for this involves energy loss to the surrounding cold water producing cold spots in the suit, however, it is important to realize that working divers also periodically bypass hot water to sea to maintain skin temperature at a comfortable level. Figure 2 shows mean skin temperature and inlet hot water temperature at constant 2.5 gpm flow for two air breathing divers wearing NRV hot water garments in 6°C water at 10 FSW. These divers were told to make themselves comfortable, and hot water temperature was adjusted accordingly. It is clear that both divers kept mean skin temperature at 33-34°C for comfort. When hot water temperature was increased to 43°C, mean skin temperature increased to as much as 39°C, which reduced skin heat loss to zero, but made the divers uncomfortably hot. Both divers asked for reduced hot water temperature, and again stabilized their mean skin temperatures at about 34°C. These mean skin temperatures are near the thermoneutral point for resting men immersed to the neck in water (13). Thermoneutrality indicates that rectal temperature is constant and most of the resting metabolic heat production is dissipated through the skin. At 1 ATA in air, this is usually assumed to be about 90% of the total heat production; the other 10% being respiratory heat loss.

Estimated resting metabolic heat production for seated men in thermally comfortable hyperbaric environments as determined in some 50 measurements during recent NEDU thermal studies is 56 ± 3 W.m^{-2}. This is in good agreement with mean values of 51 W.m^{-2} and 57 W.m^{-2} reported by other investigators for men in hyperbaric helium atmospheres (8, 11). In thermoneutral water, this value should be approximately the same, and about 90% of it, or about 50 W.m^{-2}, would be lost through the skin. This indicates that C_{sk} is minimized in hot water suits, but it is not zero or negligible. Although a resting man is comfortable at a C_{sk} of about 50 W.m^{-2} with low RHL, the effects of high RHL on comfort and metabolic heat production must be considered. Figure 3 shows changes in rectal temperature in 4 divers breathing cold helium-oxygen while sitting in a comfortable helium environment at depths between 640 and 1800 FSW. The divers in this study felt quite comfortable throughout the cold gas breathing periods despite falling rectal temperature.

It can be seen from Figure 3 that slow core cooling does not result in significant increases in metabolic heat production ($\Delta \dot{V}_{O_2}$) until T_{re} falls more than 0.65°C. The magnitude of the metabolic response when it finally appears is small, and the rate of fall of rectal temperature does not decrease, because new heat production is being offset by higher respiratory heat losses caused by increases in ventilation. In contrast, similar rectal temperature drops produced by immersing the whole body in cold helium-oxygen are associated with intense shivering and heat production approaching the rate of heat loss through the skin, but not enough heat is produced to compensate for the associated respiratory heat losses (6). Therefore, divers feel cold only at low skin temperatures. If skin temperatures are high (e.g. in a hot water suit), large amounts of heat can be lost through the respiratory tract, depressing rectal temperature, without the diver realizing it. Therefore, it must be assumed that metabolic heat production from shivering will not effectively maintain body core temperature at any level of respiratory heat loss.

The preceding paragraphs provide sufficient data to allow an estimate of the maximum permissible RHL for a resting diver by substituting the appropriate heat transfer rates into equation 1, and solving for RHL:

$$S = M - (C_{sk} + RHL) \qquad \text{(eq. 1)}$$

$$-14\ W.m^{-2} = 56\ W.m^{-2} - RHL - 50\ W.m^{-2}$$

$$RHL = 20\ W.m^{-2}$$

This value for RHL means that if the average resting diver maintains the water temperature in his hot water garment at a comfortable level, then he can lose heat through his respiratory tract at a rate of 20 $W.m^{-2}$ and drop his rectal temperature at 0.25°C per hour. This estimate of RHL includes both convective and evaporative components, however the evaporative component is small under hyperbaric conditions and decreases as a fraction of the total RHL with increasing depth at a given minute ventilation. For this reason, evaporative RHL will be neglected for the purposes of this report. This will also simplify the RHL formula (eq. 2, Appendix) by eliminating the second term of the equation. The relationship between respiratory heat loss, gas density (depth), gas temperature, and ventilation now becomes:

$$RHL = \frac{\dot{V}_E\ (\rho C_p\ \Delta T)\ (k)}{SA} \qquad \text{(eq. 2)}$$

where RHL is given in $W.m^{-2}$, $\dot{V}_E$ is minute ventilation in $\ell.min^{-1}$, ρ is gas density ($g.\ell^{-1}$), C_p is the constant pressure specific heat of the helium-oxygen mixture ($cal.g^{-1}\,^{\circ}C^{-1}$), ΔT is the difference between inspired (T_{in}) and expired (T_{ex}) gas temperatures, k is a constant (.0697) converting RHL from $cal.min^{-1}$ to $W.m^{-2}$, and SA is diver's surface area in m^2.

Of the variables in equation 2, we have set RHL at 20 $W.m^{-2}$, ρC_p is a function of depth, and $\dot{V}_E$ is normally 8-10 $\ell.min^{-1}$ for rest, and is effectively independent of depth. Using a $\dot{V}_E$ of 8 $\ell.min^{-1}$, and surface area at $2m^2$ (1) equation (2) yields a value of 72 for the product (ρC_p) (ΔT). Setting (ρC_p) (ΔT) equal to 72 and solving for ΔT in terms of (ρC_p):

$$\Delta T = 72/(\rho C_p)$$

The only remaining problem is to determine the relationship between ΔT and inspired gas temperature. Figure 4 shows T_{in} versus T_{ex} during helium-oxygen breathing, measured with a fast response thermistor over a wide range of depths and inspired gas temperatures. The relationship is approximately linear and can be expressed by the equation:

$$T_{ex} = 0.28\ T_{in} + 25.4$$

since ΔT is $T_{ex} - T_{in}$, we can solve for T_{in} in terms of ΔT:

$$\Delta T = 0.28\ T_{in} + 25.4 - T_{in}$$

$$T_{in} = 35.3 - 1.39\ \Delta T$$

By substituting the relationship $\Delta T = 72/(\rho C_p)$ for ΔT above:

$$T_{in} = 35.3 - 100/(\rho C_p)$$

Using this relationship and values of (ρC_p) from Table 1, a curve of minimum inspired gas temperatures at different depths is obtained (Figure 5). The inspired gas temperature at each depth will just produce a 0.25°C per hour rectal temperature drop in a resting diver.

When the diver exercises, minute ventilation increases from 8 $\ell.min^{-1}$ to as much as 100 or more $\ell.min^{-1}$, resulting in an increase in respiratory heat loss (eq. 2). The exercise also increases heat production, offsetting some fraction of the increase in respiratory heat loss. This fraction is the ratio of the increase in respiratory heat loss to the increase in metabolic heat production, $\Delta RHL/\Delta M$ (eq. 3, Appendix). If this ratio is less than one, $[1 - \Delta RHL/\Delta M]$ will be the fraction of the heat produced from exercise which is available to heat the body after the increase in RHL. When $\Delta RHL/\Delta M$ is equal to or greater than one, none of the heat from exercise is available to heat the body. The ratio of $\Delta RHL/\Delta M$ is proportional to the ratio of minute ventilation to oxygen consumption shown by the relationship:

$$\Delta RHL/\Delta M = \dot{V}_E/\dot{V}_{O_2} \, (\rho \, C_p) \, (\Delta T) \, (.0002) \qquad \text{(eq. 4)}$$

which is derived in the Appendix.

As long as $\Delta RHL/\Delta M$ is less than one, the diver will be able to gain some heat from exercise. Since $(\rho \, C_p)$ (ΔT) has been set at 72, eq. 4 becomes:

$$\dot{V}_E/\dot{V}_{O_2} \, (72) \, (.0002) < 1$$

or $$\dot{V}_E/\dot{V}_{O_2} < 1/.0144 < 69$$

If the ratio of $\dot{V}_E$ to $\dot{V}_{O_2}$ is less than 69, $\Delta RHL/\Delta M$ is less than one, and the diver can always gain heat by exercising. The highest $\dot{V}_E/\dot{V}_{O_2}$ ratio sustainable during exereise is about 45, indicating that any diver gains heat with exercise if his inspired gas temperature is within the limits of Figure 5.

During exercise in a hot water suit, the diver's rectal temperature would fall less than 0.25°C per hour only if skin heat flow remains at the resting level, or increases less than the net heat gain from the exercise. This is not likely because the exercising diver, responding to temperature signals at the skin, often bypasses hot water to sea to maintain a comfortable skin temperature; setting a level of skin heat loss which dissipates the excess heat produced by the exercise. The allowable respiratory heat loss of 20 $W.m^{-2}$ remains uncompensated, and the rate of rectal temperature fall remains at 0.25°C per hour.

Discussion

This report has presented the rationale for developing improved minimum inspired gas temperature limits for use by the U.S. Navy. The new proposed inspired gas temperatures are considerably warmer than the Braithwaite curve temperatures because they are based upon a value for $\rho C_p \Delta T$ of just over one half of that previously allowed. The reasons for this are evident from examining the effects of respiratory heat loss on thermal balance. The diver does not compensate well for RHL, and he does not respond with increased heat production until his rectal temperature falls significantly. The diver responds best to thermal stimuli at the skin surface, which may cause him to bypass his hot water flow during exercise because his skin feels warm. This allows him to dissipate some of the excess heat produced by the exercise; however, he is unaware of his respiratory heat losses. Although the new limits consider this problem, there is no actual data quantifying the levels of skin heat loss under various exercise conditions in divers allowed to adjust their hot water flow for comfort. Until such data is obtained, sparing use of hot water bypass is recommended.

In addition, the RHL limits outlined in this report are dependent upon the diver having adequate hot water to maintain a comfortable skin temperature for his level of exercise. For this reason, loss of hot water flow to the diver is reason to abort the excursion, as rectal temperature may decrease more than 3.0°C per hour under these conditions, depending upon water temperature and the individual's ventilatory response to cold.

In recommending Figure 5 to replace the current inspired gas temperature limits, it must be emphasized that these are still minimum inspired temperature limits. They are based only upon convective respiratory heat loss, and are predicted to allow changes in rectal temperature of up to 0.25°C per hour. The limits do not specifically address the question of cold-induced respiratory tract secretions or changes in pulmonary function, but the permitted levels of RHL are sufficiently low to minimize these problems.

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APPENDIX: Calculations

The body heat balance equation used in this study was:

$$M \pm R \pm C_{sk} \pm RHL \pm E = S$$

where

M is metabolic heat production ($W.m^{-2}$), S is storage of body heat ($W.m^{-2}$) with S negative if body heat content is falling, R is radiant heat exchange ($W.m^{-2}$), C_{sk} is cutaneous conductive plus convective heat exchange ($W.m^{-2}$), RHL is respiratory heat loss ($W.m^{-2}$), and E is evaporative heat loss ($W.m^{-2}$).

Evaporative and conductive heat exchange at the skin were considered negligible in dry helium-oxygen environments, and conductive heat loss was included in C_{sk} when considering wet environments. To determine changes in heat storage with body cooling, we rearrange the above equation:

$$S = M - (C_{sk} + R + RHL + E)$$

For a diver in a hot water garment, R and E are negligible and the equation becomes:

$$S = M - (C_{sk} + RHL) \qquad \text{(eq. 1)}$$

Total respiratory heat loss (convective plus evaporative) is calculated from the equation:

$$RHL = [\dot{V}_E \cdot \rho . C_p \cdot (T_{ex} - T_{in})] + [\dot{V}_E \cdot 580\ (\Delta P_{H_2O}/760).\ 273°K/(273+T_a)\ (0.80)]$$

where

$\dot{V}_E$ is minute ventilation in BTPS, ρ and C_p are the density and constant pressure specific heat of the helium-oxygen atmosphere; T_{ex} and T_{in} are expired and inspired gas temperatures (°C) respectively; 580 is the latent heat of vaporization of water in cal.g^{-1}; ΔP_{H_2O} is the difference between inspired and expired P_{H_2O} when expired P_{H_2O} is assumed fully saturated at T_{ex}; T_a is ambient temperature in °C; and 0.80 is water content of the gas in $g.l^{-1}$ under standard conditions. The second term of the equation, representing evaporative RHL, is neglected for the purposes of this report because it is independent of density and decreases as a fraction of the total RHL and depth increases. The simplified RHL equation becomes:

$$RHL = \dot{V}_E\ (\rho C_p)\ (T_{ex} - T_{in}) \qquad \text{(eq. 2)}$$

Oxygen consumption ($\dot{V}_{O_2}$) and carbon dioxide production ($\dot{V}_{CO_2}$) are calculated using standard equations neglecting the minute water vapor concentration at depth . $\dot{V}_{O_2}$ is converted to metabolic rate by multiplying its value by 4.9 Kcal $min^{-1}\ \ell^{-1}$ oxygen and converting to $W.m^{-2}$.

The fraction of additional heat production available for warming the body (F_M) after increases in RHL and M from exercise or shivering is:

$$F_M = 1 - \Delta RHL/\Delta M \qquad \text{(eq. 3)}$$

For heat gain to occur during exercise or shivering, F_M must be positive; a negative F_M indicates a net decrease in heat storage. Therefore, when $\Delta RHL/\Delta M < 1$, there is additional heat available for warming. The body will see this heat as excess, and the diver will attempt to dissipate it through his skin by lowering skin temperature.

The relationship between ΔRHL and ΔM can be expressed in terms of $\dot{V}_E/\dot{V}_{O_2}$ ratio by differentiating equation (2) with respect to $\dot{V}_{O_2}$:

$$\frac{dRHL}{d\dot{V}_{O_2}} = \left(\frac{d\dot{V}_E}{d\dot{V}_{O_2}}\right)[(\rho C_p)(T_{ex}-T_{in})]$$

Since $\dot{V}_E$ is a linear function of $\dot{V}_{O_2}$ with an intercept near zero, the slope (m) is therefore:

$$m = \dot{V}_E/\dot{V}_{O_2}$$

and the derivative $\frac{d\dot{V}_E}{d\dot{V}_{O_2}}$ can be approximated by $\dot{V}_E/\dot{V}_{O_2}$.

This simplifies the derivative of equation (2) with respect to $\dot{V}_{O_2}$:

$$\frac{\Delta RHL}{\Delta \dot{V}_{O_2}} = \frac{\dot{V}_E}{\dot{V}_{O_2}} [(\rho C_p)(T_{ex}-T_{in})]$$

Expressing ΔRHL and $\Delta\dot{V}_{O_2}$ in common units (watts) requires the following conversion factors:

$$\Delta RHL/\Delta M = \frac{\dot{V}_E(\rho C_p)(T_{ex}-T_{in})(.0697\ W.cal^{-1}\ min)}{\dot{V}_{O_2}(4.9\ Kcal\ .\ell^{-1})(69.7\ W.Kcal^{-1}\ min)}$$

$$\Delta RHL/\Delta M = \frac{\dot{V}_E}{\dot{V}_{O_2}}(\rho C_p)(\Delta T)(.0002) \qquad \text{(eq. 4)}$$

where $\dot{V}_E$ is .in $\ell.min^{-1}$ BTPS, $\dot{V}_{O_2}$ is in standard $\ell.min^{-1}$, ΔT is in °C and ρC_p is in $cal.\ell^{-1}.°C^{-1}$.

TABLES AND FIGURES

Table 1. Physical properties of helium-oxygen mixtures at 0°C.

Figure 1. Relationship between change in body heat content (S) and change in rectal temperature (ΔT_{re}) in 4 resting subjects breathing cold helium-oxygen while maintaining normal skin heat loss levels. Data pooled from sixteen one-hour cold gas breathing studies at depths between 640 and 1800 FSW and an inspired gas temperature of 14 ± 2°C. $\bar{T}_{sk}$ was constant at 32-33°C.

Figure 2. Inlet hot water temperatures and mean skin temperatures ($\bar{T}_{sk}$) in two resting subjects wearing NRV hot water suits for 6°C water temperature at 10 FSW.

Figure 3. Change in oxygen consumption ($\Delta \dot{V}O_2$) and change in rectal temperature (ΔT_{re}) over time in 4 subjects at each of 4 depths and a single inspired gas temperature of 14 ± 2°C. Baseline resting $\dot{V}O_2$ breathing warm gas was $.342 \pm 0.042$ slpm.

Figure 4. Inspired versus expired helium-oxygen temperatures over a wide range of gas temperatures and depths.

Figure 5. Proposed minimum inspired helium-oxygen temperatures for saturation depths between 200 and 1500 FSW.

TABLE 1: Physical Properties of Helium-Oxygen Mixtures at 0°C

DEPTH(FSW)	$F_{I_{He}}/F_{I_{O2}}$	$\rho(g.\ell^{-1})$	*$C_{P_{mix}}(cal.g^{-1}{\bullet}C^{-1})$	$\rho C_p(cal.\ell^{-1}{\bullet}C^{-1})$
200	94/6	1.785	1.180	2.106
300	96/4	2.296	1.201	2.757
400	97/3	2.818	1.212	3.414
500	97/3	3.463	1.212	4.197
600	98/2	3.869	1.221	4.724
640	98/2	3.869	1.221	4.724
700	98/2	4.473	1.221	5.462
800	98.5/1.5	4.920	1.226	6.032
900	98.5/1.5	5.502	1.226	6.745
1000	98.5/1.5	6.082	1.226	7.457
1100	99/1	6.449	1.232	7.944
1200	99/1	7.008	1.232	8.632
1300	99/1	7.564	1.232	9.317
1400	99/1	8.119	1.232	10.001
1500	99/1	8.672	1.232	10.682
1800	99.3/0.7	10.144	1.234	12.517

*P_{O_2} = 0.4 ATA

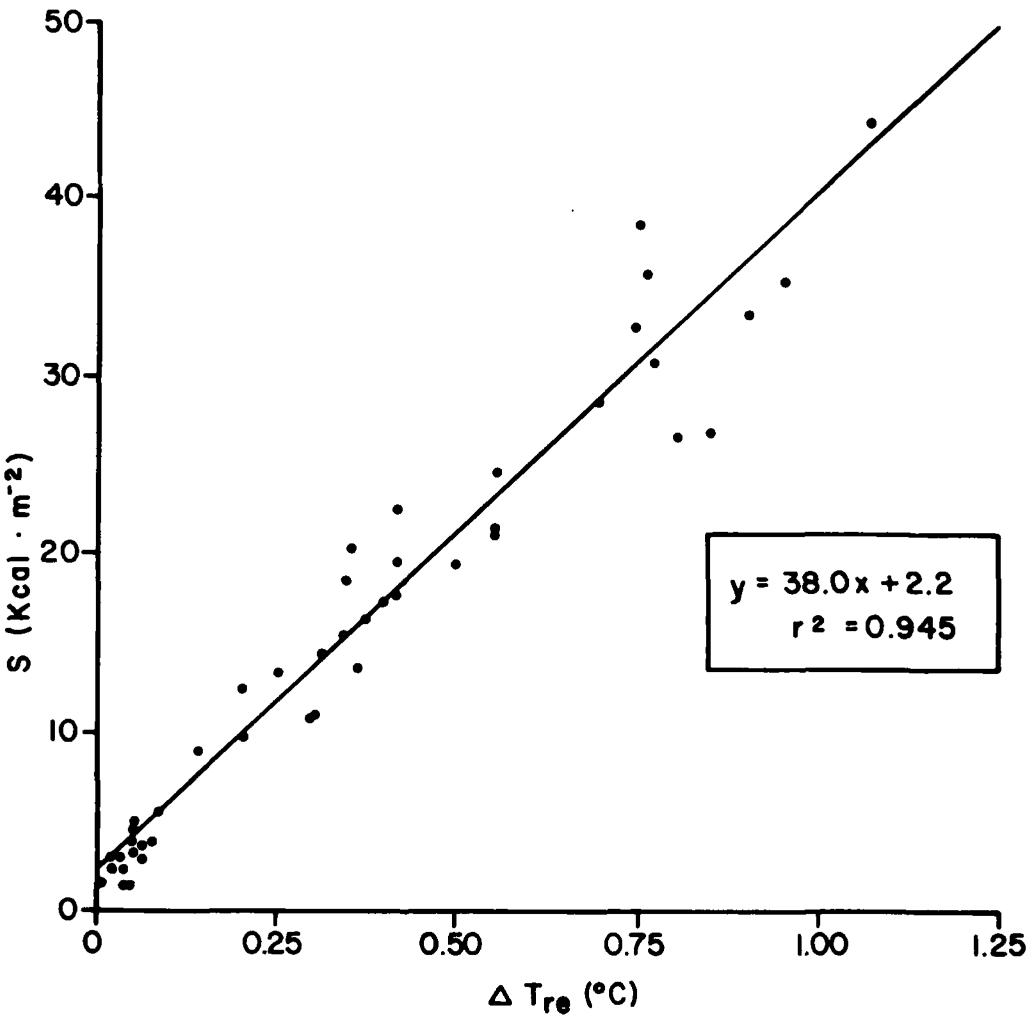


FIGURE 1. Relationship between change in body heat content (S) and change in rectal temperature (ΔT_{re}) in 4 resting subjects breathing cold helium-oxygen while maintaining normal skin heat loss.

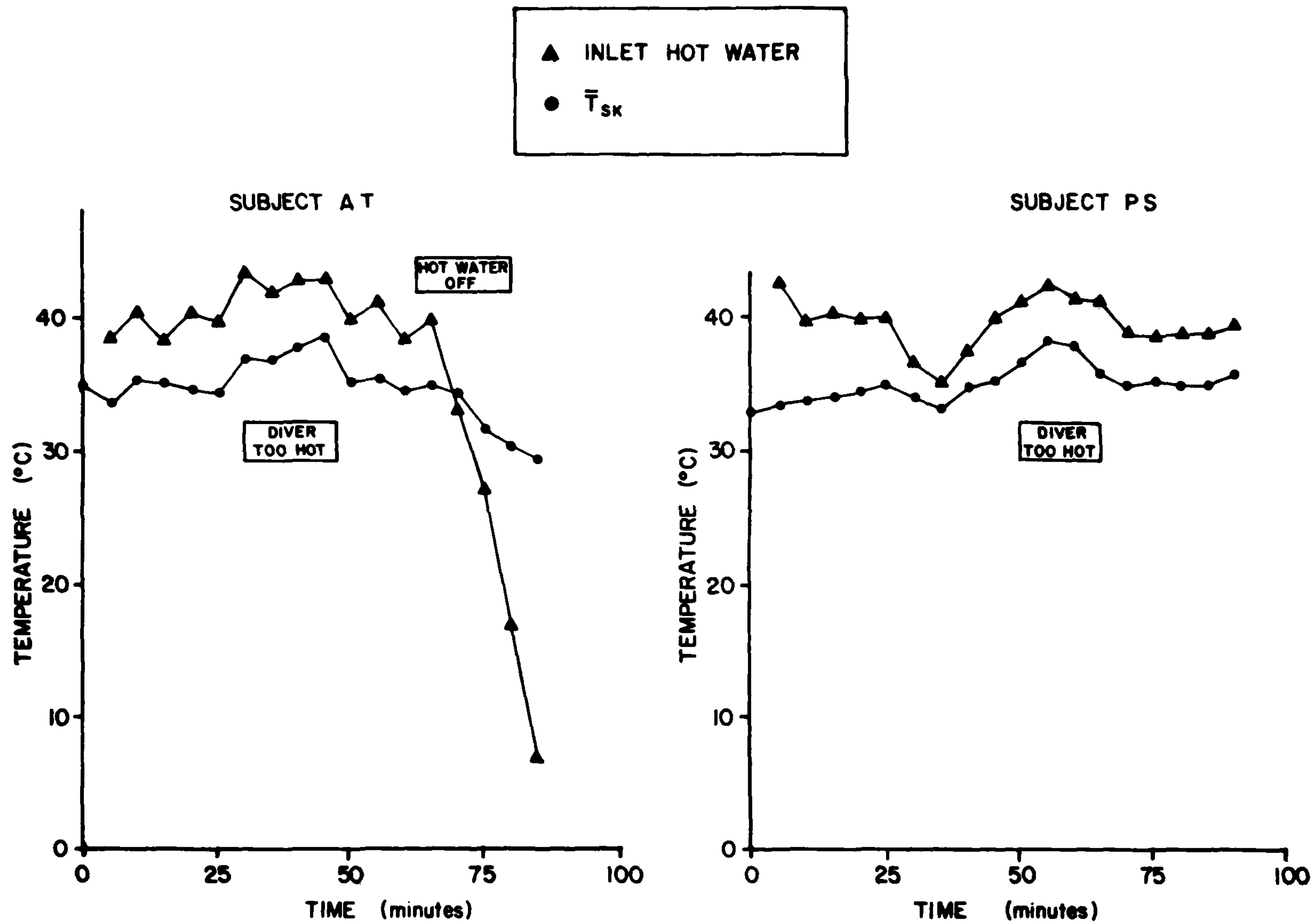


FIGURE 2. Inlet hot water temperatures and mean skin temperatures ($\bar{T}_{sk}$) in two resting subjects wearing NRV hot water suits for 6°C water temperature at 10 FSW.

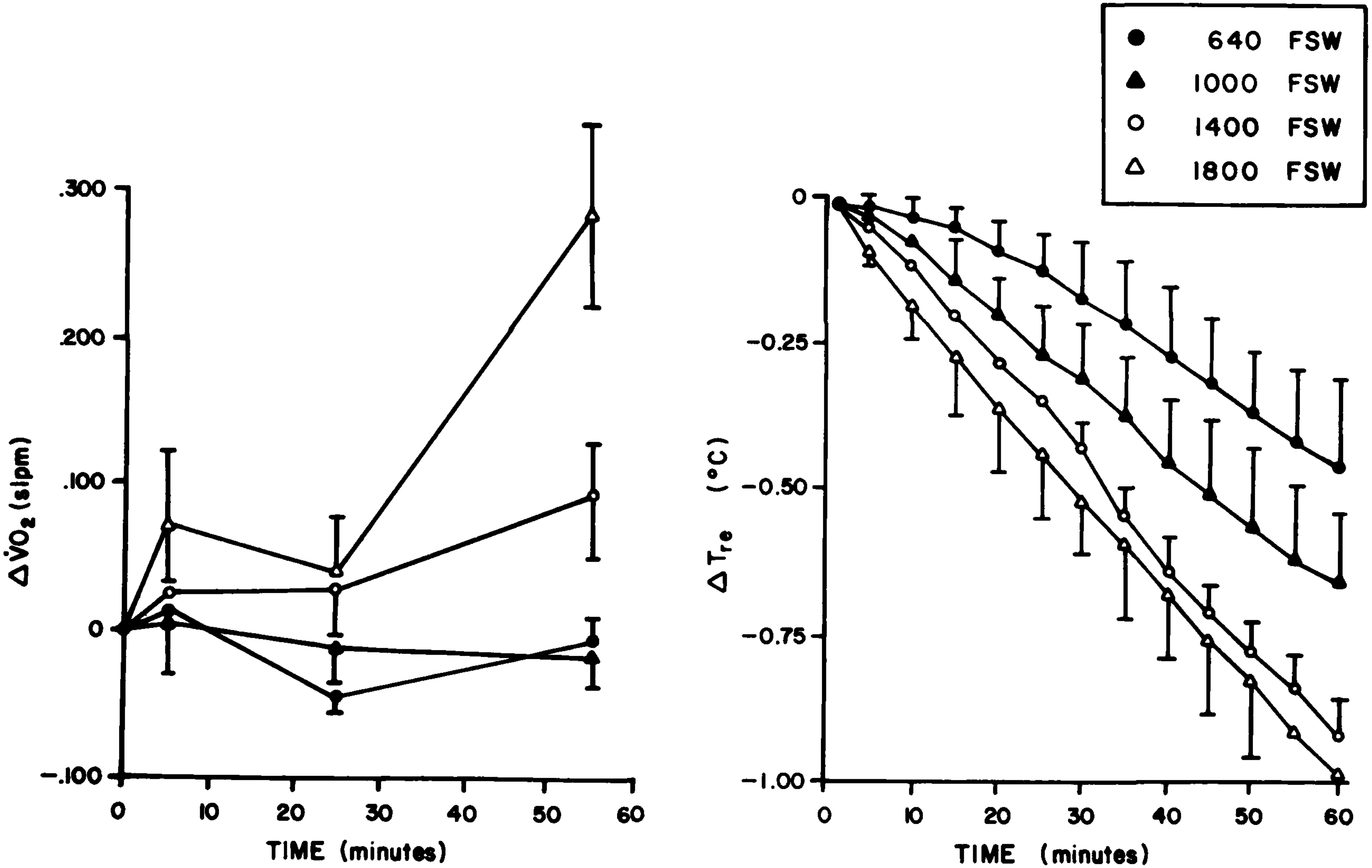


FIGURE 3. Change in oxygen consumption (ΔV_{O_2}) and change in rectal temperature (ΔT_{re}) over time in 4 subjects at each of 4 depths and a single inspired gas temperature of 14 ± 2°C. Baseline resting V_{O_2} breathing warm gas was $.342 \pm 0.042$ slpm.

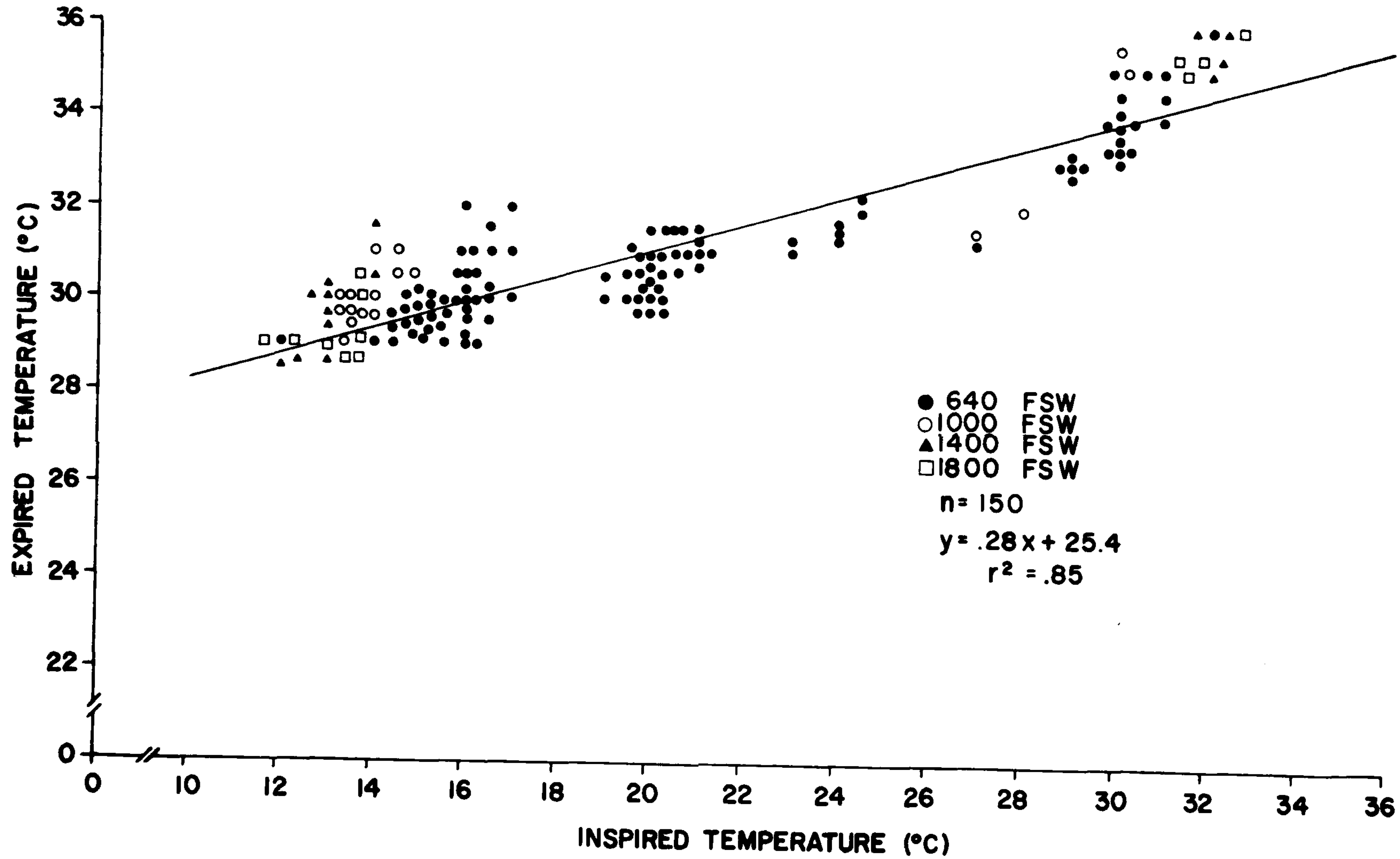
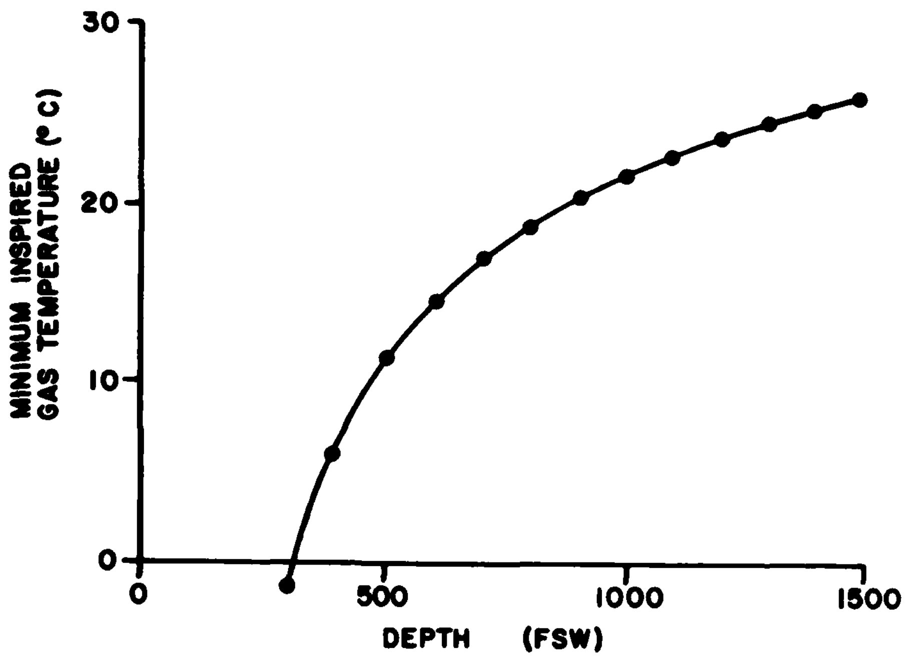


FIGURE 4. Inspired versus expired helium-oxygen temperatures over a wide range of gas temperatures and depths.



DEPTH (FSW)	MINIMUM INSPIRED GAS TEMPERATURE (°C)	(°F)
300	-1.0	30.2
400	6.0	42.8
500	11.5	52.7
600	14.1	57.9
700	17.0	62.6
800	18.7	65.7
900	20.5	68.9
1000	21.9	71.4
1100	22.7	72.9
1200	23.7	74.7
1300	24.6	76.3
1400	25.3	77.5
1500	25.9	78.6

FIGURE 5. Proposed minimum inspired helium-oxygen temperatures for saturation depths between 300 and 1500 FSW.