CNS calculations in rebreathers: their formal modelling, implementation and safety.

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Revision History

Revision	Date	Description
A	10th Oct 2005	CNS Model, Review.
B	14th Jan 2006	Cleared for issue
C	2nd June 2008	(C1, 14th April 2006). 2^13 is defined instead of 10000 (C2, 18th April 2006). [15 15 19 24 30 38 46 57 65 70 76 83 91 101 114 164 303] /s is defined instead of [19 19 23 29 37 46 56 69 79 85 93 101 111 123 139 201 370] %/s The above update simplifies the calculation of the total CNS. Instead of dividing the SUM of dCNS by 10000 it is possible to use right shift. (C3, 2nd June 2008). Further accident data considered.

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1. PURPOSE AND SCOPE

This document reports the formal modelling of CNS calculations in rebreather: both the specification and implementation models where floating point is avoided.

These models form the central nervous system (CNS) oxygen toxicity model used in the Deep Life Rebreather Virtual Test Bench (VTB).

Formal models are used by Deep Life as a specification against which implementations are validated. As such, the model is a safety tool. In that context, the scope of this document is broadened from a strict consideration of the formal model, to include a brief discussion of appropriate safe CNS limits for sports rebreather applications.

2. SUMMARY

Erik C. Baker [1] describes precise methods to calculate CNS as a function of the actual oxygen partial pressure (PO_2) and the actual time of exposure.

A model for the Baker equation is provided along with a simplified version which avoids the calculation of CNS fractions and logarithmic functions.

Consideration is also given to the scaling factors, or conservatism factors, that should be applied with depth or inert gases to enable a diver to keep the risk of O2 convulsions at a "very unlikely" level. This is based on recent research on the antagonistic effects of depth, helium and carbon dioxide, as well as an analysis of the statistical risk based on the results of published trials using US Navy CNS tables.

3. ERIC C. BAKER METHOD

Central Nervous System (CNS) Toxicity is one of two main forms of oxygen toxicity: the other being pulmonary toxicity. The method in universal use by divers to "track" CNS oxygen toxicity is to compute a "CNS fraction" for each segment of the dive profile and then sum up these results to produce a total CNS fraction for the dive. These fractions are often multiplied by 100 and expressed as a percentage (CNS %). A CNS fraction is calculated by taking the time spent at a given PO2 and dividing by the NOAA time limit for that PO2. When the CNS fractions from all segments of the dive profile add up to 1 (or 100%) then the overall limit for CNS oxygen toxicity has been reached for that dive.

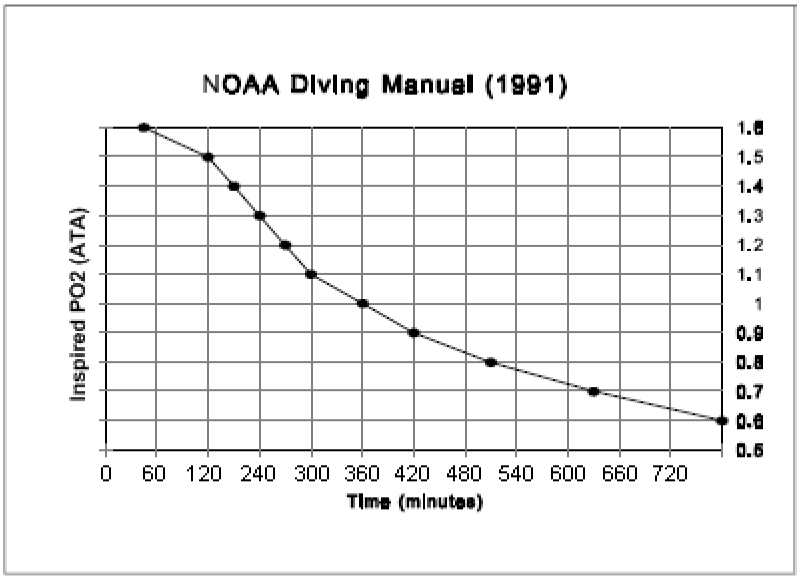


Figure 1. CNS limits established by Dr. Bill Hamilton and colleagues in the NOAA Repetitive Excursions (REPEX) Procedures Report [1].

For a constant depth profile (in which the PO2 remains constant), the CNS fraction is calculated by

$$CNS\_fraction = \frac{time\_at\_PO2}{time\_Limit\_for\_PO2}$$

For an ascent or descent profile at a constant rate (where the PO2 varies at a constant rate), the CNS fraction for a given PO2 range with a linear time limit function can be calculated by

$$CNS\_fraction = \frac{\ln\left|T_{\mathrm{lim}} + mkt_x\right| * \ln\left|T_{\mathrm{lim}}\right|}{mk}$$

where m is the slope of the linear time limit function, k is the constant rate of change in PO2 with

time, T_{lim} is the initial time limit for the interval shown in **Figure 1**, and t_x is the time of exposure over the interval.

The curve of **Figure 1** calculated as the time limit function of PPO2 is shown in **Figure 2** where the PPO2 is [0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6]; CNS time limit is [900 720 570 450 360 300 240 210 180 150 120 45].

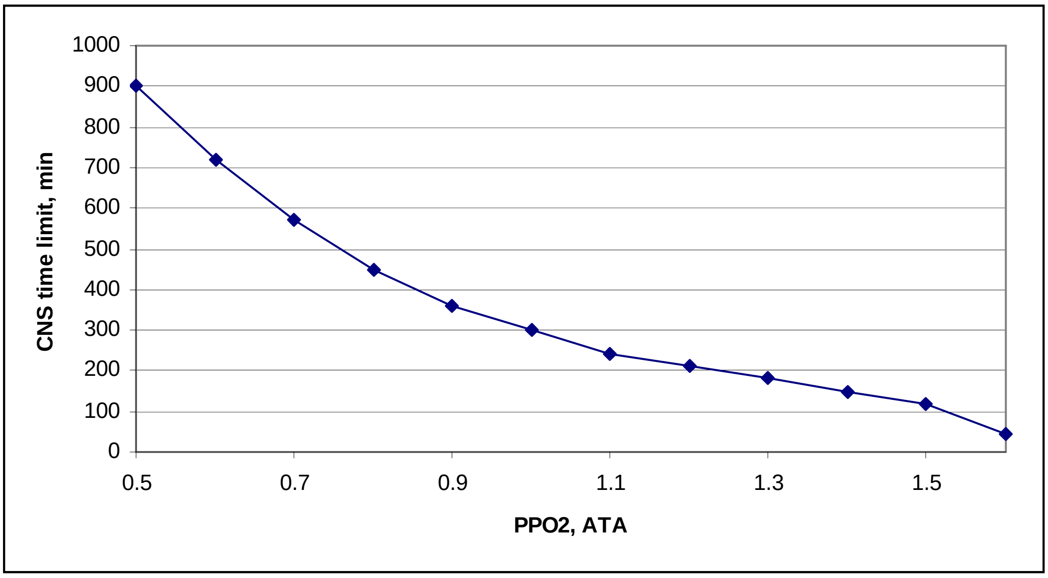


Figure 2. Time limit function of PPO2

Erik C. Baker made one extrapolation to describe a time limit equation for the PO2 range from 0.5 to 0.6 in order to complete the series. An individual equation is written as:

$$Time\_Limit = m * PPO2 + b\,,$$

where m is the slope of the line and b is the intercept for the given PO2 range (**Table 1**).

Table 1. Coefficients for the series of linear equations

PPO2, ATA	m (slope)	b (intercept)
0.5 - 0.6	-1800	1800
0.6 - 0.7	-1500	1620

0.7 - 0.8	-1200	1410
0.8 - 0.9	-900	1170
0.9 - 1.1	-600	900
1.1 - 1.5	-300	570
1.5 - 1.6	-750	1245

Calculation of $Time\_Limit$ within a PO2 range applies when the present PO2 is greater than the lower limit of the PO2 range and is less than or equal to the upper limit of the PO2 range.

Note: The above equations of Eric C. Baker method combine the data points of the NOAA Diving Manual (1991) (see **Figure 1**) and NOAA Diving Manual (2001) [**Table 2**] for CNS oxygen toxicity and provide the identical results for the data of both manuals.

Example Calculation of Eric C. Baker [1]:
Consider the following dive profile using EAN 32 for the gas mix (ignore decompression considerations for this example):

Segment 1 Descent from 0 fsw to 120 fsw at 40 fsw/min
Segment 2 Constant depth at 120 fsw for 22 min
Segment 3 Long, slow ascent from 120 fsw to 0 fsw at -4 fsw/min

What is the CNS fraction accumulated on this dive? Program solution:

For Segment 1Program calculates a CNS fraction = .0090
For Segment 2Program calculates a CNS fraction = .1761
For Segment 3Program calculates a CNS fraction = .0895

Total CNS fraction for this dive = .0090 + .1761 + .0895 **= .2746 = 27.5%**

Note: If PO2 < 0.5 then the calculation does not apply

4. SUGGESTED METHOD OF CNS CALCULATION

Lets consider, for example, the CNS for the constant PPO2 of 1 using the time limit function of PPO2 shown in **Figure 2**. The time limit for PPO2 of one is 300 min. It means that CNS reaches 10, 50 and 100% in 30, 150 and 300 minutes respectively. The weight of CNS increases at 1/3 % each minute. The second fraction of CNS is calculated as

$$\Delta CNS(PPO2) = \frac{100}{60 * Time\_Limit\_for\_PPO2}$$

The ΔCNS function of PPO2 in %/s is shown in **Figure 3** where the PPO2 is [0 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.25 1.3 1.35 1.4 1.45 1.5 1.55 1.6] ATA; ΔCNS is [1/540 1/540 1/432 1/342 1/270 1/216 1/180 1/144 1/126 1/117 1/108 1/99 1/90 1/81 1/72 10/498 1/27] %/s. CNS fractions of PO2 < 0.5 are zero.

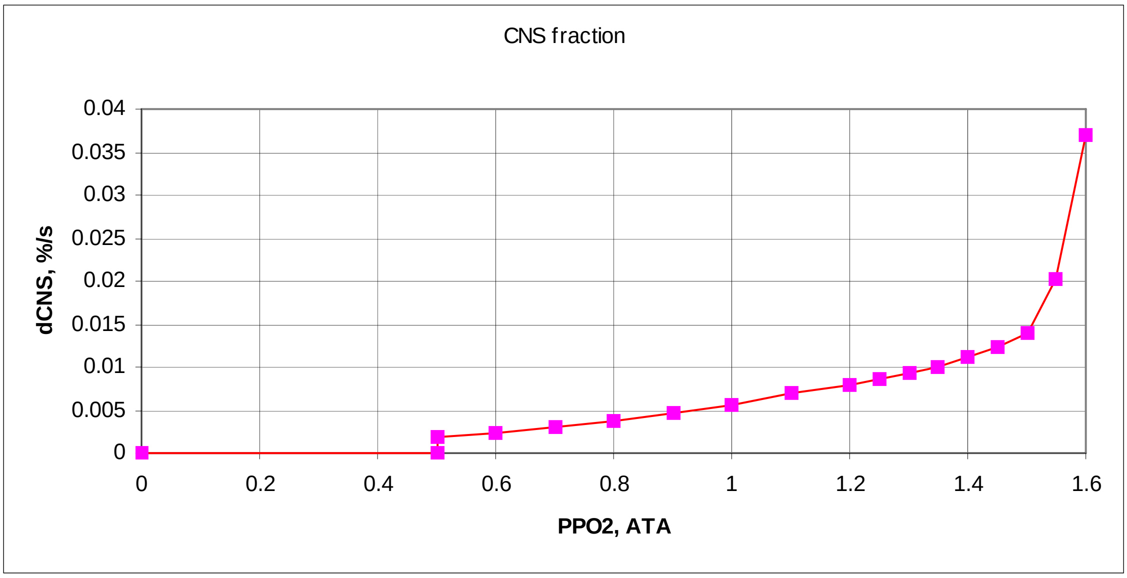


Figure 3. CNS fraction as function of PPO2 in %/s

The CNS as function of PPO2 and time can be calculated as

$$CNS(PPO2,t) = \sum \Delta CNS(PPO2(n * \Delta t)) \text{ ,}$$

where $t = n * \Delta t$ is time of diving, Δt is 1s clock.

Calculation of CNS in the MatLAB simulink is shown in **Figure 4**. The output of the saturation block: “PPO2<1.6” is from 0 to 1.6. The discontinuity block: “dCNS” is ΔCNS function of PPO2. The output of the switch: “Threshold=0.5” is zero when the PPO2 is less than 0.5 and the switch output is equal to the output of the dCNS block when the PPO2 is more or equal to 0.5. The saturation block of “CNS<100%” limits the model output inside 100%.

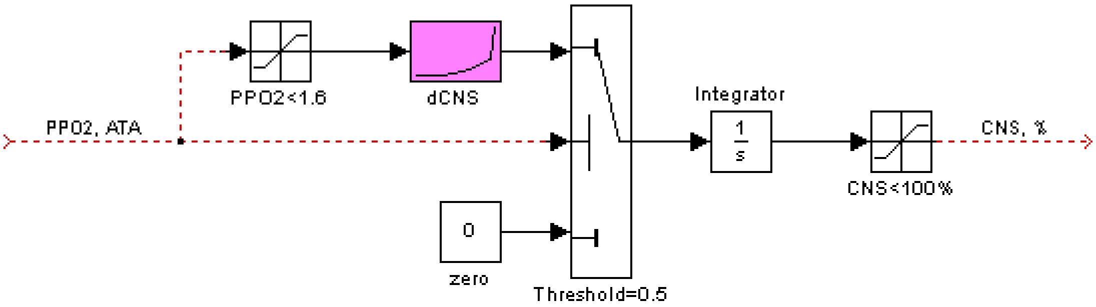


Figure 4. CNS model in MatLAB simulink

4.1 CNS calculation using integer numbers

Many implementations will use an integer implementation instead of floating point numbers, to decrease the calculation time and simplify the structures required, for example, for FPGA implementations. To save CNS accuracy the vector of ΔCNS would normally be multiplied 10000 times and then the sum of the CNS fractions must be divided in the same amount.

The integer ΔCNS function of PPO2 per second is

PPO2 = [0 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.25 1.3 1.35 1.4 1.45 1.5 1.55 1.6] ATA;

ΔCNS =[15 15 19 24 30 38 46 57 65 70 76 83 91 101 114 164 303] /s.

5. COMPARE RESULTS OF THE FLOATING AND INTEGER METHODS

The following data of dive profile [1] is used to compare Erik C. Baker and the suggested method.

1. Descent from 0 fsw to 120 fsw at 40 fsw/min. PPO2 from 0.32 ATA to 1.484
2. Constant depth at 120 fsw for 22 min. PPO2 is 1.484 ATA
3. Long, slow ascent from 120 fsw to 0 fsw at -4 fsw/min PPO2 from 1.484 ATA to 0.32

In the MatLAB format given below, the total CNS of the dive profile is 27.78%. It is the base CNS value. The CNS fractions are calculated for current PPO2 and the corresponding time limit each second. Increasing the time resolution does not change the total CNS value.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
CNS = 0;

for t = 1:3300      % 1 s time resolution

    % PPO2
    if t <= 180     % Descent from 0 fsw to 120 fsw at 40 fsw/min
                    % PPO2 from 0.32 ATA to 1.484 ATA
        PPO2 = 0.32 + (1.484-0.32)*t/180;
    end
    if t > 180 && t <= 1500 % Constant depth  at 120 fsw for 22 min
        PPO2 = 1.484;       % in ATA
    end
    if t > 1500     % Ascent from 120 fsw to 0 fsw at 4 fsw/min
                    % PPO2 from 1.484 ATA to 0.32 ATA
        PPO2 = 1.484 - (1.484-0.32)*(t-1500)/1800;
    end

    % Time limit and CNS increment: dCNS
    if PPO2 < 0.5
        dCNS = 0;
    end
    if PPO2 >= 0.5 && PPO2 < 0.6
        CNS_TL = 1800 - 1800*PPO2;
        dCNS = 100/(60*CNS_TL);
    end
    if PPO2 >= 0.6 && PPO2 < 0.7
        CNS_TL = 1620 - 1500*PPO2;
        dCNS = 100/(60*CNS_TL);
    end
    if PPO2 >= 0.7 && PPO2 < 0.8
        CNS_TL = 1410 - 1200*PPO2;
        dCNS = 100/(60*CNS_TL);
    end
    if PPO2 >= 0.8 && PPO2 < 0.9
        CNS_TL = 1170 - 900*PPO2;
        dCNS = 100/(60*CNS_TL);
    end
    if PPO2 >= 0.9 && PPO2 < 1.1
        CNS_TL = 900 - 600*PPO2;
        dCNS = 100/(60*CNS_TL);
    end
    if PPO2 >= 1.1 && PPO2 < 1.5
```

```
        CNS_TL = 570 - 300*PPO2;
        dCNS = 100/(60*CNS_TL);
    end
    if PPO2 >= 1.5 && PPO2 < 1.6
        CNS_TL = 1245 - 750*PPO2;
        dCNS = 100/(60*CNS_TL);
    end

    % total CNS
    CNS = CNS + dCNS;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

The total CNS of the suggested method for the compared dive profile is 27.87% for the float calculation and 27% for the calculation of integer numbers as shown in **Figure 5**.

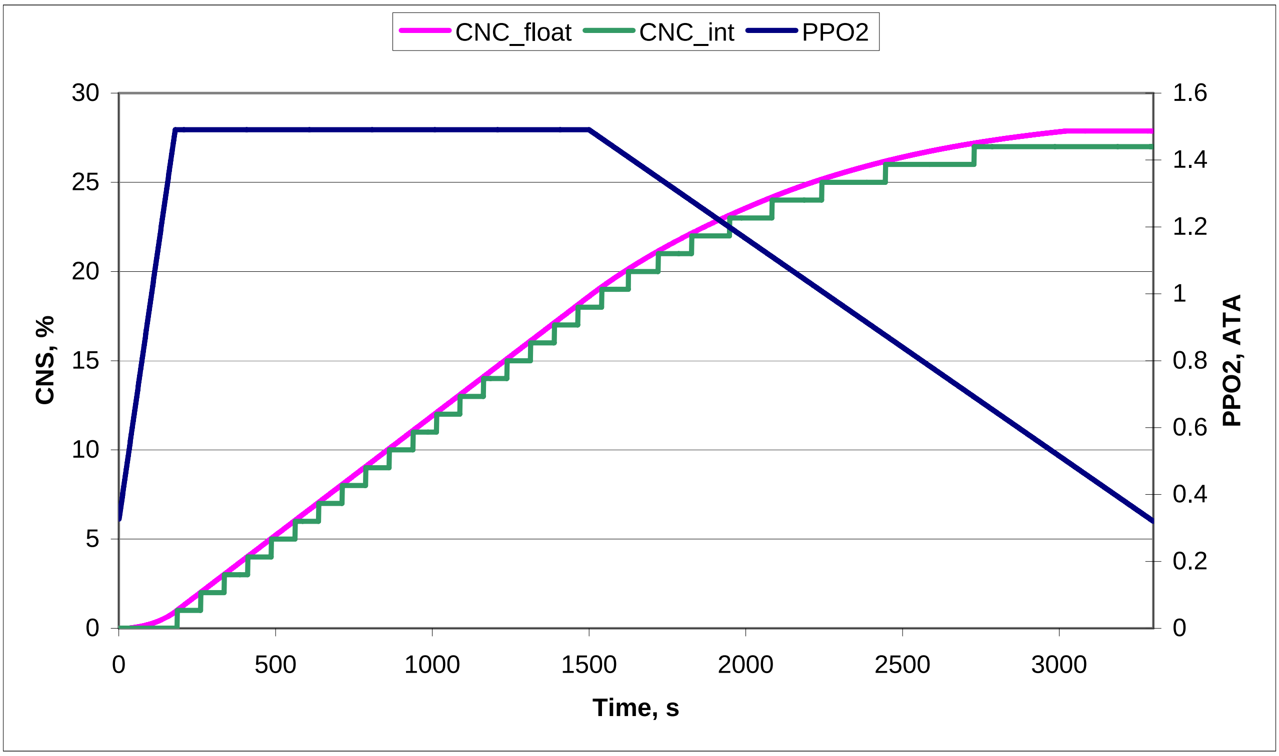


Figure 5. PPO2 profile of Erik C. Baker and the suggested CNS calculated in float and integer data format

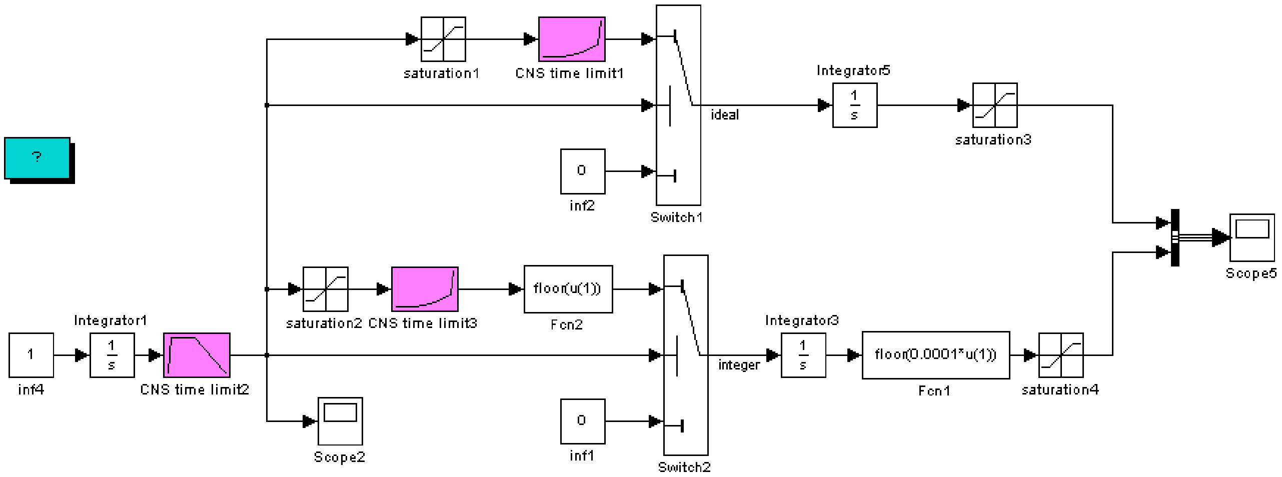


Figure 6. CNS simulink model for calculation with float and integer data

6. SUMMARY ON THE INTEGER METHOD OF CALCULATING CNS

1. The integer method calculates CNS as sum of the CNS fractions that is a function of PPO2. The weigh of each fraction is inversely proportional to the NOAA time limit and in direct proportion to the calculation clock.
2. The integer method does not contains logarithmic functions and the division in calculation of CNS fraction.
3. The accuracy of the integer method relative to the method of Erik C. Baker applied to the same dive profile is 0.3% (27.87-27.78)/27.78 for the calculation with the float numbers and it is 1% for the integer numbers.

7. NECESSARY DEGREE OF CONSERVATIVE MARGIN

The next issue for a formal model, is what down rating is required for sports diving use. The Baker tables are based on US Navy tests, where just under 1% of divers have O2 toxicity symptoms when diving to 75% of the maximum CNS rating.

Appropriate limits for a diver are very different from limits in a dry recompression chamber. The occupants of a chamber will have a very low workload, will be warm and comfortable. The exposure may the thousands of times higher than for a sports diver in the water: some of the most extreme sports technical divers are even decompressing in a bell on such a high multiple.

Multiple factors indicate the Baker CNS limits are too high for general sports diving use, including:

1. Accidents. Six accidents involving O2 toxicity are reported on the RBW forum and there are indicators that the real number of incidents is much higher. Given the small number of rebreathers in use, this is level of risk is nowhere close to the requirements mandated for safety critical systems. The O2 convulsion incident level is estimated at between 1 in 10,000 hours and 1 in 100,000 hours in the CCR community, based on these reports alone. A PPO2 set point of 1.3 is the most commonly used: surveys on RBW refer.
2. Increased risk from deep diving [7], possibly due increased CO2 retention.
3. Increased risk from use of helium [6], due to mechanisms that are not understood.

4. Very highly increased risk from CO2 retention, either from higher CO2 inhalation as a result of scrubber breakthrough, scrubber bypass, mouthpiece volume, non-ideal flapper valves, or other forms of CO2 retention from Work of Breathing or CO2 retainers [5]. It is noted that sports divers are having CNS hits using PPO2s as low as 1.0, with just 25% of the standard Baker exposure: this is almost certainly due to these effects.
5. US Navy tests [8], [9]
6. The margin of accuracy of the PPO2 measurement.

Given these risk factors, it is recommended that the CNS algorithm be executed with 0.2 added to the measured PPO2. This means a PPO2 of 1.2 is treated like a PPO2 of 1.4 for the purposes of CNS calculation for the sports diver. For increased conservatism, figures of up to 0.3 could be added. This does extend dive times, particularly decompression time.

These figures are based on the small numbers of observed CNS accidents and diver-years exposure. The small numbers in these statistics (there is less than 10,000 diver-years of exposure, where a diver-year is the amount of sports diving a sports diver performs in a year).

It is recommended that the user have an option of aggressive CNS or conservative CNS: the former adding 0.2, the latter adding 0.3 to the measured PPO2.

The reduction in the probability of O2 toxicity from a given change in the PPO2 can be estimated based on the statistical curves published by Harabin et. Al [8] It is likely that adding 0.3 to the CNS calculation would reduce the incidence of O2 convulsions by 10^7, moving the incidence rate from to over 1 billion hours.

For commercial divers, where a full face helmet is used, the aggressive and conservative margins can be reduced, to 0.1 and 0.2 respectively. The latter is recommended.

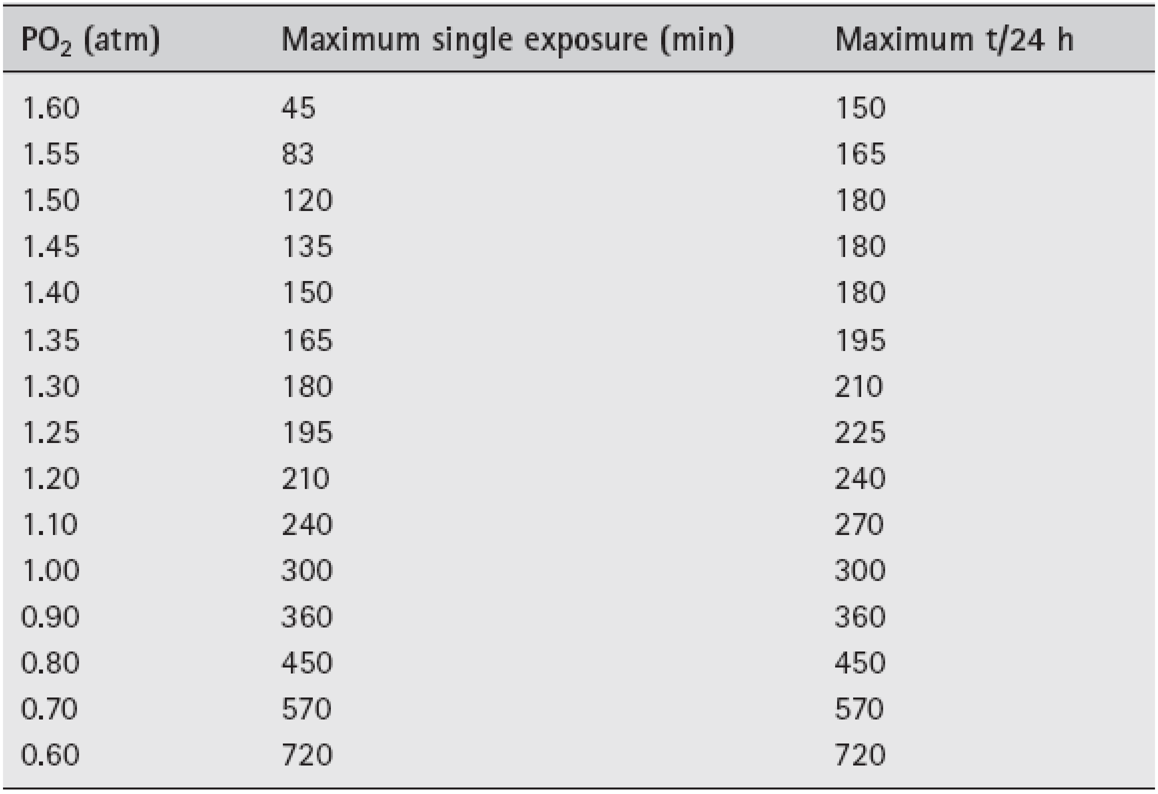
The effect of the conservatism figures here, is to accelerate the CNS clock such that the chance of a sample appearing outside the distribution is probably less than 1 in 10^-9: again the limited numbers on which these statistics are based has to be recognised. This risk figure is based on extrapolations from available data and the data in the papers we have referenced. It does not prevent the diver using a higher PPO2 for short periods during decompression: the clock is an integral intended to indicate cumulative damage.

Consideration should be given to limiting the maximum PPO2 that can be set for dives below 20m to 1.1m, for the same reasons. The PPO2 may increase during decompression to 1.3, but there is very little gain above that: of course, the PPO2 is limited for the longest decompression stages (at 6msw to 3msw), by basic gas laws.

This simple means to provide CNS guard-banding for safety purposes, is trivial to implement. As such it has considerable merits over other methods that would change the whole form of the CNS limit curves.

APPENDIX.

Table 2 NOAA oxygen exposure limits. The Table gives limits in min fora single PO2 exposure level, and for each day (24 h). (NOAA Diving Manual 2001, Figs 15.2, 16.2) [2]



PO_2 (atm)	Maximum single exposure (min)	Maximum t/24 h
1.60	45	150
1.55	83	165
1.50	120	180
1.45	135	180
1.40	150	180
1.35	165	195
1.30	180	210
1.25	195	225
1.20	210	240
1.10	240	270
1.00	300	300
0.90	360	360
0.80	450	450
0.70	570	570
0.60	720	720

REFERENCES

The use of academic references has been avoided. References listed are minimised, and chosen from papers which are readily available on the internet.

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