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A MODEL OF DRY DECK SHELTER CO₂ LEVELS

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TECHNICAL REVIEW AND APPROVAL

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The experiments reported herein were conducted according to the principles set forth in the current edition of the "Guide for the Care and Use of Laboratory Animals," Institute of Laboratory Animal Resources, National Research Council, National Academy Press, 1996."

This technical report has been reviewed by the NMRC scientific and public affairs staff and is approved for publication. It is releasable to the National Technical Information Service where it will be available to the general public, including foreign nations.

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13. ABSTRACT (Maximum 200 words) To maintain a safe environment, the partial pressure of carbon dioxide (CO ₂) in a closed space needs to be kept under control. In the dry deck shelter (DDS) the CO ₂ pressure is controlled primarily through the use of venting of each of the three modules. Air from the submarine air banks, which contain less than 1250 ppm CO ₂ , is added to a compartment at the same time that an exhaust valve is open, allowing a constant pressure to be maintained in the compartment. This report will provide details of a model of the CO ₂ partial pressure in a DDS. The model assumes that the gas spaces are well mixed, containing a uniform concentration of CO ₂ within a given compartment. Each gas space has the following elements as parameters: the number of divers in the compartment, the average rate of CO ₂ production by each diver, the ambient pressure in the compartment, the effective gas space volume (accounting for the degree to which the compartment is flooded with water), the temperature of the compartment, the venting cycle time, the flow rate of the venting gas, and the concentration of CO ₂ in the supply (ventilation) gas. In addition to a detailed description of the model and its limitations, this report includes details on the application of the model to operational conditions and data for CO ₂ levels in a DDS, and the computer code used to make the comparison.				
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BACKGROUND

The dry deck shelter (DDS) is a three-compartment unit, which can be mated to a submarine for operations. These three compartments, the hanger, transfer trunk, and chamber, are described below.

- (1) Hanger: With a dry volume $\approx 1400 \text{ ft}^3$, it is the largest of the three compartments. It has a large hatch at the aft end, which allows for the ingress and egress of the divers and their equipment. The hanger can be pressurized independently and flooded with water to various depths.
- (2) Transfer Trunk: Connected at the aft end to the hanger, the trunk is mated to the submarine. Transfer of men and equipment between the submarine and the DDS is through a hatch in the floor, and may need to be done when the hanger is flooded and open to the sea. Since the submarine is maintained at a pressure of 1 atmosphere absolute (ATA), the trunk is often cycled between the dry (1 ATA) state of the submarine and the wet (pressurized) state of the hanger. Its pressurization and flood capabilities are the same as the hanger.
- (3) Chamber: The chamber is attached to the forward end of the trunk. It is outfitted for DCS treatment and can be independently pressurized to any depth required for treatment.

During operations, varying numbers of divers are present in the compartments, each producing CO_2 and consuming O_2 . It is especially important to control the level of CO_2 in the trunk, where there may be 7 or 8 divers breathing in a $50\text{-}100 \text{ ft}^3$ air space (when the trunk is flooded). Since the level of CO_2 is not currently measured, this control is accomplished by periodically venting the compartment. Air from the submarine air banks is let into the compartment at the same time as air is being bled out, back into the submarine. This procedure is apparently effective, but has two drawbacks: it requires a large amount of air and is very noisy.

The former makes keeping the air banks charged difficult and the latter hinders communication within the DDS. For both reasons, it is desirable to minimize the amount of venting required.

We will derive the equations that describe the amount of CO₂ within a compartment and then apply those equations to the problem of periodic ventilation of a closed compartment. Finally, we will compare the predictions of the equations with some measurements of CO₂ levels in a DDS from actual Fleet operations.

DERIVATION

We will calculate the partial pressure of CO₂ in a given compartment by determining the number of moles of CO₂ in the compartment, assuming that the ideal gas law holds. The DDS is operated to depths of 165 feet of seawater (fsw), allowing for a maximum gas pressure of 6 ATA. This is within the range of validity of the ideal gas law. If we assume that the respiratory quotient is unity, then each mole of O₂ used by a diver leads to the release of a mole of CO₂. Thus, the only change in the total number of gas molecules in the compartment is due to the flow of air into or out of the compartment.

$$\frac{dn_{tot}}{dt} = F_{in} - F_{out} \equiv F$$

where n_{tot} is the total number of moles of gas in the compartment, and F_{in} and F_{out} are the the number of moles per second flowing into or out of the compartment, respectively. The net flow into the compartment is F .

Carbon dioxide levels in a compartment change due to three different mechanisms: introduction, production, or elimination. Carbon dioxide is introduced by the inflowing air from the submarine air banks, which contain air with an upper limit of 1250 ppm CO₂ (the submarine

is usually ventilated using surface air before the air banks are pressurized, so the actual CO₂ concentration is often substantially below this level). Produced by divers that are present in the compartment, CO₂ is eliminated by venting. (We do not consider the elimination of CO₂ by scrubbing. This technique is used on occasion, and only in the chamber portion of the DDS.) Thus, we can write for the number of moles of CO₂

$$\frac{dn_{CO_2}}{dt} = C_{in} \cdot F_{in} + N_{diver} \cdot A - \frac{n_{CO_2}}{n_{tot}} \cdot F_{out}$$

where n_{CO_2} is the number of moles of CO₂ in the compartment, C_{in} is the mole fraction of CO₂ in the inflowing gas, N_{diver} is the number of divers in the compartment, A is the average rate of production of CO₂ by a diver (in moles per second), and the ratio n_{CO_2}/n_{tot} is the mole fraction of CO₂ in the gas in the compartment. This final term implies that the gas in the compartment is well-mixed.

There are four cases of interest (Some sub-categories may also be explored below).

- a) $F_{out} = 0, \quad F = 0 \Rightarrow F_{in} = 0$
(constant pressure in the compartment with no venting)
- b) $F_{out} = 0, \quad F \neq 0 \Rightarrow F_{in} \neq 0$
(pressure in the compartment is increasing)
- c) $F_{out} > 0, \quad F = 0 \Rightarrow F_{in} = F_{out}$
(venting the compartment at constant pressure)
- d) $F_{out} > 0, \quad F \neq 0 \Rightarrow F_{in} \neq F_{out}$
(venting the compartment while changing the pressure)

In order to simplify the discussion below, we make the following definitions:

$$\begin{aligned} X_1 &= n_{tot} \\ X_2 &= n_{CO_2} \\ B &= C_{in} \cdot F_{in} + N_{diver} \cdot A \\ C &= F_{out} \end{aligned}$$

The above equations then become

$$\frac{dx_1}{dt} = F$$

$$\frac{dx_2}{dt} = B - \frac{x_2}{x_1} \cdot C$$

Case a) $F_{\text{out}} = F_{\text{in}} = F = 0 \Rightarrow C = 0$

$$\frac{dx_1}{dt} = 0 \Rightarrow x_1 = x_{10}$$

$$\frac{dx_2}{dt} = B \Rightarrow x_2 = x_{20} + B \cdot t$$

where x_{10} and x_{20} are the initial values of x_1 and x_2 , respectively. Thus, the total number of moles of gas is constant and the number of moles of CO_2 increases linearly in time. Since $F_{\text{in}} = 0$, the rate of increase of CO_2 depends only upon the number of divers and their rate of CO_2 production ($B = N_{\text{diver}} \cdot A$).

Case b) $F_{\text{out}} = 0 = C, \quad F = F_{\text{in}} \neq 0$

$$\frac{dx_1}{dt} = F_{\text{in}} \Rightarrow x_1 = x_{10} + F_{\text{in}} \cdot t$$

$$\frac{dx_2}{dt} = B \Rightarrow x_2 = x_{20} + B \cdot t = x_{20} + (C_{\text{in}} \cdot F_{\text{in}} + N_{\text{diver}} \cdot A) \cdot t$$

Thus, with only inflowing gas both the total number of moles of gas and the number of moles of CO_2 increase linearly as a function of time.

Case c) $F_{\text{out}} > 0, \quad F = 0 \Rightarrow F_{\text{in}} = F_{\text{out}}$

$$\frac{dx_1}{dt} = 0 \Rightarrow x_1 = x_{10}$$

$$\frac{dx_2}{dt} = B - \frac{x_2}{x_{10}} \cdot C \Rightarrow x_2 = \frac{B}{C} \cdot x_{10} \cdot \left(1 - e^{-\frac{C}{x_{10}}t} \right) + x_{20} \cdot e^{-\frac{C}{x_{10}}t}$$

This is the case where the compartment is being ventilated. Thus the mole fraction of CO₂ in the compartment exponentially approaches the ratio B/C, where

$$\frac{B}{C} = \frac{C_{in} \cdot F_{in} + N_{diver} \cdot A}{F_{out}}$$

The higher the rates of production and introduction relative to elimination, the higher the asymptotic level of CO₂

Case d) $F_{out} > 0, \quad F \neq 0 \Rightarrow F_{in} \neq F_{out}$

$$\frac{dx_1}{dt} = F \Rightarrow x_1 = x_{10} + F \cdot t$$

$$\frac{dx_2}{dt} = B - C \cdot \frac{x_2}{x_1} = B - \frac{C \cdot x_2}{x_{10} + F \cdot t}$$

We can solve this equation for x₂ by changing variables. First, let t' = x₁₀ + F*t, so that dt' = F*dt, and

$$\frac{dx_2}{dt'} = B' - C' \cdot \frac{x_2}{t'}$$

where B' = B/F and C' = C/F. This equation is now separable. If we do a change of variable a second time, defining v = x₂/t', then this equation becomes

$$\frac{dt'}{t'} = \frac{dv}{B' - (1+C') \cdot v}$$

Consider two cases, $F_{in} = 0$ and $F_{in} > 0$.

Subcase d1) $F_{in} = 0 \Rightarrow C' = C/F = F_{out}/(F_{in} - F_{out}) = -1$, so that

$$\frac{dt'}{t'} = \frac{dv}{B'}$$

or

$$v = B' \cdot \ln(t') + v_0$$

Substituting for v and t' from above yields

$$\frac{x_2}{x_{10} + F \cdot t} = \frac{B'}{F} \cdot \ln(x_{10} + F \cdot t) + v_0$$

$$x_2 = \left(\frac{B'}{F} \cdot \ln(x_{10} + F \cdot t) + v_0 \right) \cdot (x_{10} + F \cdot t)$$

At time $t = 0$, $x_2 = x_{20}$, so that

$$x_{20} = \left(\frac{N_{diver} \cdot A}{F_{out}} \cdot \ln\left(\frac{x_{10}}{x_{10} - F_{out} \cdot t}\right) + \frac{x_{20}}{x_{10}} \right) (x_{10} - F_{out} \cdot t)$$

Subcase d2) $F_{in} > 0$, $F \neq 0$, so that

$$\frac{dt'}{t'} = \frac{dv}{B' - (1+C') \cdot v}$$

$$\ln(t') = \frac{-1}{(1+C')} \cdot \ln(B' - (1+C') \cdot v) + D_0$$

where D_0 is a constant of integration. Substituting in $v = x_2/t'$ and rearranging gives

$$x_2 = \frac{B'}{1+C'} \cdot t' - D_0 \cdot t'^{-C'}$$

At time $t = 0$, $t' = x_{10}$, $x_2 = x_{20}$, and

$$D_0 = \left(\frac{B'}{1+C'} \cdot x_{10} - x_{20} \right) \cdot x_{10}^{C'}$$

Then

$$x_2 = \frac{B'}{1+C'} \cdot t' - \left(\frac{B'}{1+C'} \cdot x_{10} - x_{20} \right) \cdot \left(\frac{x_{10}}{t'} \right)^{C'}$$

Upon substitution back to the original variables

$$x_2 = \frac{B}{F_{in}} \cdot (x_{10} - (F_{in} - F_{out}) \cdot t) - \left(\frac{B}{F_{in}} \cdot x_{10} - x_{20} \right) \cdot \left(\frac{x_{10}}{x_{10} - (F_{in} - F_{out}) \cdot t} \right)^{\frac{F_{out}}{F_{in} - F_{out}}}$$

where $B = N_{diver} \cdot A + C_{in} \cdot F_{in}$. Note that this case corresponds to the simultaneous venting of the chamber while the pressure is changing (assuming that the volume of the compartment is fixed).

The partial pressure of CO_2 can now be determined using the ideal gas law

$$P_{CO_2} = \frac{R_g \cdot T}{V} \cdot x_2$$

where R_g is the gas constant, T is the absolute temperature, and V is the gas volume.

VENTING

During operations, venting usually takes place when other factors, N_{diver} , V , and P (total gas pressure), are being held constant. Thus, between vents, when there is no flow into or out of the compartment, Case a) above describes the buildup of CO_2 in the compartment. During venting, the inflow and outflow are balanced (constant P), and Case c) applies. Ventilation occurs periodically, repeating after time t_{cycle} , with ventilation lasting for time t_{vent} . Define

$$E = e^{-\frac{F_{out}}{x_{10}} \cdot t_{vent}}$$

$$E' = 1 - E$$

Then the number of moles of CO_2 at the end of a vent is given by

$$x_2^{off} = \frac{N_{diver} \cdot A + C_{in} \cdot F_{in}}{F_{out}} \cdot x_{10} \cdot E' + x_2^{on} \cdot E$$

where the superscript indicates that the venting gas was turned off or on at that point in time.

During the nonventing period, Case a) applies. Therefore, at the end of a non-venting period we can write

$$x_{2,i}^{on} = x_{2,i}^{off} + N_{diver} \cdot A \cdot (t_{cycle} - t_{vent})$$

We can combine these equations to generate recursive relations describing the CO₂ level at the beginning and end of each vent cycle in terms of the levels of the previous cycle.

So,

$$x_{2,i}^{off} = \frac{N_{diver} \cdot A + C_{in} \cdot F_{in}}{F_{out}} \cdot x_{10} \cdot E + \left(x_{2,i-1}^{off} + N_{diver} \cdot A \cdot (t_{cycle} - t_{vent}) \right) \cdot E$$

$$x_{2,i}^{on} = \frac{N_{diver} \cdot A + C_{in} \cdot F_{in}}{F_{out}} \cdot x_{10} \cdot E + x_{2,i-1}^{on} \cdot E + N_{diver} \cdot A \cdot (t_{cycle} - t_{vent})$$

In order to simplify this, let

$$G = E \cdot x_{10} \cdot \frac{N_{diver} \cdot A + C_{in} \cdot F_{in}}{F_{out}}$$

and

$$H = N_{diver} \cdot A \cdot (t_{cycle} - t_{vent})$$

Then

$$x_{2,i}^{off} = G + E \cdot H + E \cdot x_{2,i-1}^{off}$$

$$x_{2,i}^{on} = G + H + E \cdot x_{2,i-1}^{on}$$

Both of these equations are of the form

$$f_i = a \cdot f_{i-1} + b$$

Which can be rewritten in terms of the initial value f_0

$$f_i = a^i \cdot f_0 + \frac{1-a^i}{1-a} \cdot b$$

We can determine the asymptotic value for this expression by letting the number of cycles go to infinity. Because $E < 1$, $a^i = E^i \rightarrow 0$, and

$$x_{2,\infty}^{off} = \frac{G+E \cdot H}{1-E}$$

$$x_{2,\infty}^{on} = \frac{G+H}{1-E}$$

the difference between these two is simply $H = N_{diver} \cdot A \cdot (t_{cycle} - t_{vent})$, which is the amount of CO_2 produced by the divers during the nonventing period.

Using this expression for $x_{2,\infty}^{on}$, and assuming we know the upper limit of CO_2 partial pressure (either 0.015 ATA, or possibly 0.02 ATA), we can determine the venting time necessary to maintain CO_2 partial pressure below this value by solving for t_{vent} in the transcendental equation

$$(1-E) \cdot P_{2,\infty}^{on} = \left((1-E) \cdot x_{10} \cdot \frac{N_{diver} \cdot A + C_{in} \cdot F_{in}}{F_{out}} + N_{diver} \cdot A \cdot (t_{cycle} - t_{vent}) \right) \cdot \frac{R \cdot T}{V}$$

where $P_{2,\infty}^{on}$ is the CO_2 partial pressure limit.

Appendix A contains the source code for program TABLE.FOR, which uses the above equation to solve for venting times in each of the 4 gas volumes present during DDS operations. These 4 gas volumes are the chamber, the trunk, the hanger, and the bubble. The bubble is the forward portion of the hanger that remains gas-filled when the rest of the hanger has been fully flooded. It contains the controls for venting the hanger, and is separated from the rest of the hanger by a plexiglass partition that is attached to the upper portion of the hanger. Also included

in Appendix A are a sample input file for the program, and 4 sample venting tables generated by the program. Note that the program uses an IMSL FORTRAN subroutine DZBREN to find the venting times from the transcendental equation. Other equation-solving routines can be used in its place.

Appendix B contains the source code for program MODEL.FOR, which uses the entire set of equations above to model expected CO₂ concentrations during the operation of a DDS. Also included are sample input and output files, and some comparisons to data from actual DDS operations. Note that this program has been designed to be used only for the transfer trunk, since this compartment is the one for which the most detailed operational data is available.


```

c
    pco2max = pco2max*p0pa
    aaa=a
    tcycle = tcycle*60.d0
c convert a from liter/min to mol/sec
    a = a/(rgas*temp)/60.d0/1000.d0*p0pa
c
c set up arrays for printing of table. depths are from current tables
c
    depth(1)=9.d0
    flows(1)=38.d0
    depth(2)=29.d0
    flows(2)=160.d0
    depth(3)=100.d0
    if(ichamb.eq.1)depth(3)=66.d0
    flows(3)=240.d0
    depth(4)=165.d0
    if((ichamb.eq.1).or.(ichamb.eq.4))depth(4)=130.d0
    flows(4)=240.d0
c
c convert compartment volume to cubic meters, set maximum number
c of divers for the compartment, and open the output file
c
    if(ichamb.eq.1) then
        vol = 1400.d0*ftm3
        ndmax = 20
        open(unit=4, file='hanger.tab',type='new')
    else if(ichamb.eq.2)then
        vol = 120.d0*ftm3
        ndmax = 8
        open(unit=4, file='trunk.tab',type='new')
    else if(ichamb.eq.3)then
        vol = 170.d0*ftm3
        ndmax = 8
        open(unit=4, file='chamber.tab',type='new')
    else if(ichamb.eq.4)then
        vol = 120.d0*ftm3
        ndmax = 4
        open(unit=4, file='bubble.tab',type='new')
    else
        write(6,110)
110    format(' improper compartment number - stop program')
        stop
    end if
c
    cppm = cppm/1.d6
    errabs = 0.d0
    errrel = 1.d-6
    do 10 id=1,4
        depthdds=depth(id)
c convert flows from cu ft/min to mol/sec
        flow=flows(id)*ftm3*p0pa/rgt/60.d0
c
c calculate ambient pressure (in pascal), total moles of gas in
c the compartment, and the time constant for the compartment

```

```

c
    pamb = (depthdds/33.d0 + 1.d0)*p0pa
    x10 = pamb*vol/rgt
    k = flow/x10
c
    do 20 nd=1,ndmax
        ndart = nd*a*rgt
        nda = nd*a
c
c calculate coefficients for equation in the DDS report
c
        c0 = (1 - E) cinf + dinf*(tcycle - tvent)
c
c where E = dexp(-k*tvent)
c
        dinf = ndart/p0pa/vol
        cinf = (pamb*(nda+cppm*flow)/flow - pco2max)/p0pa
        tlow = 0.d0
        thigh = 1.d4
        maxfn = 10000
c
c dzbren is an IMSL FORTRAN root finding routine
c
        call dzbren(func,errabs,errrel,tlow,thigh,maxfn)
        vtable(id,nd)=thigh
        imin(id,nd)=thigh/60.d0
        isec(id,nd)=thigh-60.d0*imin(id,nd)+1
20    continue
10    continue
    volf=vol/ftm3
    jmax=ndmax
    if(ichamb.eq.1)then
        write(4,181)volf,aaa,co2limit
181    format(/' HANGER, unflooded, volume = ,f6.1,' cu. ft./
1 ' O2 consumption = ,f5.2,' liter/min/'
2 ' CO2 limit = ,f6.3,' atm'/)
    else if(ichamb.eq.4)then
        write(4,184)volf,aaa,co2limit
184    format(/' BUBBLE, water depth = 4.5 ft, volume = ,f6.1,
1 ' cu. ft./
2 ' O2 consumption = ,f5.2,' liter/min/'
3 ' CO2 limit = ,f6.3,' atm'/)
    else if(ichamb.eq.2)then
        write(4,182)volf,aaa,co2limit
182    format(/' TRUNK, water depth = 4.5 ft, volume = ,f6.1,
1 ' cu. ft./
2 ' O2 consumption = ,f5.2,' liter/min/'
3 ' CO2 limit = ,f6.3,' atm'/)
    else if(ichamb.eq.3)then
        write(4,183)volf,aaa,co2limit
183    format(/' CHAMBER, unflooded, volume = ,f6.1,' cu. ft./
1 ' O2 consumption = ,f5.2,' liter/min/'
2 ' CO2 limit = ,f6.3,' atm'/)
    end if
    if(ichamb.eq.1)write(4,191)

```

```

        if(ichamb.eq.2)write(4,190)
        if(ichamb.eq.3)write(4,190)
        if(ichamb.eq.4)write(4,194)
190    format(/' # Divers',16x,DEPTH(FSW)'/
1      0 - 9   10 - 29   30 - 100   101 - 165',
2      38 SCFM  160 SCFM  240 SCFM  240 SCFM')
191    format(/' # Divers',16x,DEPTH(FSW)'/
1      0 - 9   10 - 29   30 - 66   67 - 130',
2      38 SCFM  160 SCFM  240 SCFM  240 SCFM')
194    format(/' # Divers',16x,DEPTH(FSW)'/
1      0 - 9   10 - 29   30 - 100   101 - 130',
2      38 SCFM  160 SCFM  240 SCFM  240 SCFM')
        write(4,200)(j,(imin(1,j),isec(1,j),l=1,4),j=1,jmax)
200    format(20(2x,i3,5x,4(i3,2h',i2,1h",5x)/))
        stop
        end
c
        real*8 function func(x)
        implicit real*8 (a-h,o-z)
        common/comf/c,d,xk,xc
        func = (1.d0 - dexp(-xk*x))*c + d*(xc - x)
        return
        end
c

```

End of source code for program TABLE.FOR

Sample input file TABLE.INP for program TABLE.FOR

3
1.25d0
0.015d0
1250.d0
5.d0

read(3,100)ichamb,a,pco2max,cppm,tcycle

End of sample input file TABLE.INP

Table 1. Sample Output File HANGER.TAB From Program TABLE.FOR

<i>Diver No.</i>	<i>Depth (FSW)</i>			
	<i>0 - 9 38 SCFM</i>	<i>10 - 29 160 SCFM</i>	<i>30 - 66 240 SCFM</i>	<i>67 - 130 240 SCFM</i>
1	0' 34"	0' 13"	0' 15"	0' 32"
2	1' 7"	0' 25"	0' 30"	1' 3"
3	1' 41"	0' 38"	0' 45"	1' 35"
4	2' 15"	0' 51"	1' 1"	2' 7"
5	2' 48"	1' 4"	1' 16"	2' 38"
6	3' 21"	1' 16"	1' 31"	3' 10"
7	3' 54"	1' 29"	1' 47"	3' 40"
8	4' 27"	1' 42"	2' 2"	4' 11"
9	4' 58"	1' 55"	2' 18"	4' 40"
10	5' 29"	2' 8"	2' 33"	5' 9"
11	5' 60"	2' 21"	2' 48"	5' 36"
12	6' 29"	2' 34"	3' 3"	6' 3"
13	6' 58"	2' 46"	3' 18"	6' 28"
14	7' 25"	2' 59"	3' 33"	6' 53"
15	7' 52"	3' 12"	3' 47"	7' 16"
16	8' 18"	3' 24"	4' 1"	7' 39"
17	8' 43"	3' 36"	4' 15"	7' 60"
18	9' 7"	3' 48"	4' 29"	8' 20"
19	9' 30"	3' 60"	4' 42"	8' 40"
20	9' 52"	4' 12"	4' 56"	8' 58"

Hanger, water depth = 0.0 volume = 1400.0

O₂ consumption = 1.25 liter/min

SCFM = standard cubic feet per minute

Tcycle = 5 min

Table 2. Sample output file TRUNK.TAB from program TABLE.FOR

<i>Diver No.</i>	<i>Depth (FSW)</i>			
	<i>0 - 9 38 SCFM</i>	<i>10 - 29 160 SCFM</i>	<i>30 - 100 240 SCFM</i>	<i>101 - 165 240 SCFM</i>
1	0' 36"	0' 14"	0' 25"	0' 50"
2	1' 15"	0' 29"	0' 54"	1' 47"
3	1' 55"	0' 47"	1' 26"	2' 44"
4	2' 36"	1' 7"	2' 1"	3' 33"
5	3' 13"	1' 28"	2' 34"	4' 12"
6	3' 46"	1' 51"	3' 4"	4' 42"
7	4' 14"	2' 14"	3' 29"	5' 5"
8	4' 38"	2' 35"	3' 51"	5' 23"

Trunk, water depth = 0.0 volume = 120.0; O₂ consumption = 1.25 liter/min Tcycle = 5 min

Table 3. Sample output file CHAMBER.TAB from program TABLE.FOR

<i>Diver No.</i>	<i>Depth (FSW)</i>			
	<i>0 - 9 38 SCFM</i>	<i>10 - 29 160 SCFM</i>	<i>30 - 100 240 SCFM</i>	<i>101 - 165 240 SCFM</i>
1	0' 35"	0' 13"	0' 24"	0' 48"
2	1' 12"	0' 28"	0' 51"	1' 41"
3	1' 50"	0' 43"	1' 20"	2' 34"
4	2' 28"	0' 60"	1' 50"	3' 23"
5	3' 5"	1' 18"	2' 20"	4' 4"
6	3' 38"	1' 37"	2' 48"	4' 38"
7	4' 8"	1' 56"	3' 14"	5' 6"
8	4' 35"	2' 15"	3' 37"	5' 28"

CHAMBER, unflooded, volume = 170.0 cu. ft.; O₂ consumption = 1.25 liter/min; CO₂ limit = 0.015 atm Tcycle = 5 min

Table 4. Sample output file BUBBLE.TAB from program TABLE.FOR

<i>Diver No.</i>	<i>Depth (FSW)</i>			
	<i>0 - 9 38 SCFM</i>	<i>10 - 29 160 SCFM</i>	<i>30 - 100 240 SCFM</i>	<i>101 - 130 240 SCFM</i>
1	0' 36"	0' 14"	0' 25"	0' 35"
2	1' 15"	0' 29"	0' 54"	1' 15"
3	1' 55"	0' 47"	1' 26"	1' 58"
4	2' 36"	1' 7"	2' 1"	2' 41"

BUBBLE, water depth = 4.5 ft, volume = 120.0 cu. ft.; O₂ consumption = 1.25 liter/min; CO₂ limit = 0.015 atm Tcycle = 5 min


```

c
rtrunk = (240.d0*3.d0/4.d0/pi)**(1.d0/3.d0)*ftm

p0pa = 1.01325d5 ! 1atm in pascals
p0= 1.d0 ! 1 atm pressure for reference
fsw0=33.d0 ! 1atm in fsw
t=0.d0 ! initializing
pamb010=10.d0/fsw0*p0pa
pamb1030=30.d0*p0pa
vent010=38.d0/60.d0/rgf/temp0
vent1030=160.d0/60.d0/rgf/temp0
vent30=240.d0/60.d0/rgf/temp0

c
c read in parameters
c
read (1,*) nnode ! number of nodes in profile
read (1,*) a ! oxygen consumption rate (liter/min)
read (1,*) cin ! concentration co2 in ppm in venting gas
read (1,*) cout ! initial conc. co2 in ppm in chamber
a = a/(rgl*temp0)/60.d0 ! convert to mol/sec
cin=cin/1.d6
cout=cout/1.d6
c fvent=fvent/60.d0/rgf/temp0 ! change from SCFM to mol/sec
c
c will assume that venting lasts for the entire period from the current
c node to the next node, assuming that venting is off by the next node.
c this requires that when ivent(k) = 1, tmin(k+1)=tmin(k)+tvent
c
do 10 i=1,nnode
read(1,11)tmin(i),fsw(i),dwater(i),ndiver(i),ivent(i)
pamb(i)=(fsw(i)+fsw0)/fsw0*p0pa
dwater(i)=dwater(i)*ftm
vol(i)=vtrunk(dwater(i))
tsec(i)=tmin(i)*60.d0
10 continue
11 format(3f10.2,2i10,f10.2)
do 12 i=1,nnode-1
fin(i)=zed
fout(i)=zed
delt=tsec(i+1)-tsec(i)
c
c assume that chamber volume and pressure do not change simultaneously
c nor do such changes occur during venting
c
c calculate fin and fout for changes in ambient pressure
c
dpambdt(i)=(pamb(i+1)-pamb(i))/delt
if(dpambdt(i).gt.1.d-8)then
fin(i)=vol(i)*dpambdt(i)/rgast
else if(dpambdt(i).lt.(-1.d-8))then
fout(i)= -vol(i)*dpambdt(i)/rgast
end if
c
c calculate fin and fout for changes in volume
c

```



```

        dvdt(i)=(vol(i+1)-vol(i))/delt
        if(dvdt(i).gt.1.d-8)then
            fin(i)=pamb(i)*dvdt(i)/rgast
        else if(dvdt(i).lt.(-1.d-8))then
            fout(i)= -pamb(i)*dvdt(i)/rgast
        end if
c
c calculate fin and fout for venting
c
        if(ivent(i).eq.1)then
            fin(i)=fventfcn(pamb(i))
            fout(i)=fin(i)
        end if
12 continue
    tout=0.d0
    delt=60.d0
c
c calculate the co2 partial pressures at each of the nodes
c in the profile
c
    ngas(1)=pamb(1)*vol(1)/rgast
    nco2(1)=cout*ngas(1)
    do 200 leg=1,nnode-1
        nda=ndiver(leg)*a
        fint=fin(leg)
        foutt=fout(leg)
        fnet=fint-foutt
        cnet=foutt
        bnet=cin*fint+nda
        delt=tsec(leg+1)-tsec(leg)
        x10=ngas(leg)
        x20=nco2(leg)
c
c cases (a) & (b): fout=c=0,
c
        if(dabs(cnet).lt.1.d-8)then
            ngas(leg+1)=f1case(x10,fnet,delt)
            nco2(leg+1)=f2casea(x20,bnet,delt)
        end if
c
c case (c): fout=c>0, f=0 -> fin=fout
c
        if((dabs(cnet).ge.1.d-8).and.(dabs(fnet).lt.1.d-8))then
            ngas(leg+1)=x10
            nco2(leg+1)=f2casec(x20,x10,bnet,cnet,delt)
        end if
c
c case (d): fout=c>0, fin > 0, f <> 0
c
        if((dabs(cnet).ge.1.d-8).and.(dabs(fnet).ge.1.d-8))then
            if(dabs(fint).lt.1.d-8)then
                ngas(leg+1)=x10-cnet*delt
                nco2(leg+1)=f2cased1(x20,x10,bnet,cnet,delt)
            else if(dabs(fint).ge.1.d-1)then
                ngas(leg+1)=x10+fnet*delt
            end if
        end if
    end do

```


Sample input file MODEL.INP for program MODEL.FOR

```
31, ! number of nodes in profile
0.85d0, ! oxygen consumption rate in liter/min/diver
10.d0,! co2 conc. in ppm in venting gas
6300.d0, ! initial co2 conc. in ppm in chamber
0.d0, 0.d0, 0.d0, 4, 0,
4.d0, 0.d0, 0.d0, 4, 1,
5.18d0, 0.d0, 0.d0, 4, 0,
8.d0, 0.d0, 4.d0, 4, 0,
9.d0, 0.d0, 4.d0, 4, 1,
10.18d0, 0.d0, 4.d0, 4, 0,
12.d0, 0.d0, 4.d0, 4, 0,
14.d0, 20.d0, 4.d0, 4, 0,
15.d0, 30.d0, 4.d0, 4, 0,
16.d0, 30.d0, 4.d0, 4, 0,
21.d0, 30.d0, 4.d0, 4, 0,
25.d0, 30.d0, 0.d0, 4, 1,
26.d0, 30.d0, 0.d0, 4, 0,
28.d0, 30.d0, 0.d0, 4, 0,
31.d0, 30.d0, 0.d0, 4, 1,
32.d0, 30.d0, 0.d0, 4, 0,
33.d0, 30.d0, 0.d0, 4, 0,
36.d0, 30.d0, 0.d0, 4, 1,
37.d0, 30.d0, 0.d0, 4, 0,
42.d0, 0.d0, 0.d0, 4, 1,
43.18d0, 0.d0, 0.d0, 4, 0,
47.d0, 0.d0, 0.d0, 4, 0,
48.18d0, 0.d0, 0.d0, 4, 0,
50.d0, 0.d0, 4.d0, 4, 0,
53.d0, 30.d0, 4.d0, 4, 0,
54.d0, 30.d0, 4.d0, 4, 0,
55.d0, 30.d0, 4.d0, 4, 0,
57.d0, 30.d0, 4.d0, 4, 0,
58.d0, 30.d0, 4.d0, 4, 1,
59.d0, 30.d0, 4.d0, 4, 0,
60.d0, 30.d0, 4.d0, 4, 0,

read (1,*) nnode ! number of nodes in profile
read (1,*) a ! oxygen consumption rate
read (1,*) cin ! concentration co2 in ppm in venting gas
read(1,11)tmin(i),fsw(i),dwater(i),ndiver(i),ivent(i)
```

End of sample input file MODEL.INP

The next several pages include an actual input data file (TM071797.INP) that was used for the program MODEL.FOR, the data sheets from which the input file was derived, the output file (TO071797.OUT), and a plot of the calculated CO₂ levels along with the values measured using the CO₂ analyzer. This particular data set was chosen due to its richness. The person recording the data did an excellent job, especially in recording the duration of the venting periods. Note that there are several uncertainties in the data: (1) The depth of water in the trunk is an estimate, (2) the total volume of the unflooded trunk is estimated and does not take into account the space taken up by personnel or equipment that is being transferred, (all of which lead to uncertainty in the gas volume), and (3) the concentration of CO₂ in the venting gas is unknown. For this particular input file, CO₂ was assumed to be present at a very low level of 10 ppm.

Data file TO071797.INP

66, ! number of nodes in profile
0.85d0, ! oxygen consumption rate in liter/min/diver
10.d0, ! co2 conc. in ppm in venting gas
4650.d0, ! initial co2 conc. in ppm in chamber
0.,0.,0.,2,1,4650,0.77
0.77,0.,0.,2,0.,
6.,0.,0.,2,1,4340,0.77
6.77,0.,0.,2,0.,
14.,0.,3.,2,1,3960,0.33
14.33,0.,3.,2,0.,
21.,0.,3.5,2,1,6040,0.68
21.68,0.,3.5,2,0.,
29.,0.,5.5,2,1,9220,0.77
29.77,0.,5.5,2,0.,
36.,0.,5.5,2,1,7820,0.65
36.65,0.,5.5,2,0.,
43.,0.,5.5,2,1,7060,0.82
43.82,0.,5.5,2,0.,
49.,0.,5.5,2,1,6640,0.78
49.78,0.,5.5,2,0.,
57.,0.,5.5,2,1,7280,0.75
57.75,0.,5.5,2,0.,
64.,5.,5.5,2,1,7660,0.8
64.8,5.,5.5,2,0.,
72.,5.,5.5,2,1,7680,0.52
72.52,5.,5.5,2,0.,
79.,5.,5.5,2,1,8200,0.82
79.82,5.,5.5,2,0.,
85.,5.,5.5,2,1,6140,0.52
85.52,5.,5.5,2,0.,
92.,5.,5.5,2,1,6420,0.55
92.55,5.,5.5,2,0.,
99.,5.,5.5,2,1,7000,0.97
99.97,5.,5.5,2,0.,
105.,5.,5.5,2,1,4580,0.63
105.63,5.,5.5,2,0.,
111.,5.,5.5,2,1,5240,0.77
111.77,5.,5.5,2,0.,
117.,5.,5.5,2,1,4800,0.63
117.63,5.,5.5,2,0.,
123.,5.,5.5,2,1,4840,0.73
123.73,5.,5.5,2,0.,
129.,5.,5.5,2,1,6880,0.7
129.7,5.,5.5,2,0.,
136.,5.,5.5,2,1,5900,0.92
136.92,5.,5.5,2,0.,
142.,5.,5.5,2,1,3800,0.45
142.45,5.,5.5,2,0.,
150.,5.,5.5,2,1,5700,1.05
151.05,5.,5.5,2,0.,
156.,5.,5.5,2,1,5200,0.67
156.67,5.,5.5,2,0.,

164.,5.,5.5,2,1,7000,0.43
164.43,5.,5.5,2,0,,
170.,6.,5.5,2,1,7400,0.65
170.65,6.,5.5,2,0,,
175.,6.,5.5,2,1,4720,0.63
175.63,6.,5.5,2,0,,
182.,6.,5.5,2,1,5840,0.58
182.58,6.,5.5,2,0,,
189.,6.,5.5,2,1,5600,0.47
189.47,6.,5.5,2,0,,
194.,6.,5.5,2,1,6000,0.58
194.58,6.,5.5,2,0,,
204.,6.,5.5,2,1,5840,0.58
204.58,6.,5.5,2,0,,
215.,30.,5.5,2,0,11380,
216.,40.,5.5,2,0,13240,
219.,50.,5.5,2,0,15160
221.,60.,5.5,2,0,17780

End of file TO071797.INP

Output data file TM071797.DAT

.00000	.00465	1.00000	4650.00
.77000	.00286	1.00000	2858.91
6.00000	.00425	1.00000	4247.10
6.77000	.00263	1.00000	2625.22
14.00000	.00496	1.00000	4964.50
14.33000	.00361	1.00000	3606.55
21.00000	.00649	1.00000	6485.02
21.68000	.00300	1.00000	3004.06
29.00000	.00852	1.00000	8516.59
29.77000	.00091	1.00000	914.85
36.00000	.00921	1.00000	9207.00
36.65000	.00126	1.00000	1264.69
43.00000	.00972	1.00000	9716.56
43.82000	.00089	1.00000	894.23
49.00000	.00779	1.00000	7788.83
49.78000	.00085	1.00000	850.64
57.00000	.01046	1.00000	10460.49
57.75000	.00109	1.00000	1089.71
64.00000	.00941	1.15152	9409.99
64.80000	.00121	1.15152	1206.31
72.00000	.01079	1.15152	10789.54
72.52000	.00253	1.15152	2528.59
79.00000	.01115	1.15152	11153.49
79.82000	.00130	1.15152	1300.19
85.00000	.00819	1.15152	8194.79
85.52000	.00201	1.15152	2005.67
92.00000	.01063	1.15152	10630.58
92.55000	.00232	1.15152	2315.33
99.00000	.01090	1.15152	10900.31
99.97000	.00097	1.15152	970.48
105.00000	.00767	1.15152	7665.42
105.63000	.00148	1.15152	1480.70
111.00000	.00863	1.15152	8628.19
111.77000	.00121	1.15152	1207.22
117.00000	.00817	1.15152	8168.36
117.63000	.00155	1.15152	1552.92
123.00000	.00870	1.15152	8700.41
123.73000	.00131	1.15152	1314.97
129.00000	.00833	1.15152	8329.36
129.70000	.00136	1.15152	1356.39
136.00000	.00974	1.15152	9741.71
136.92000	.00099	1.15152	990.11
142.00000	.00775	1.15152	7751.61
142.45000	.00227	1.15152	2270.77
150.00000	.01232	1.15152	12319.85
151.05000	.00091	1.15152	911.30
156.00000	.00750	1.15152	7499.77
156.67000	.00134	1.15152	1339.44
164.00000	.01110	1.15152	11095.69
164.43000	.00328	1.15152	3276.12
170.00000	.01069	1.18182	10690.11
170.65000	.00191	1.18182	1910.04

175.00000	.00770	1.18182	7699.91
175.63000	.00155	1.18182	1548.73
182.00000	.01003	1.18182	10027.22
182.58000	.00213	1.18182	2133.92
189.00000	.01068	1.18182	10678.97
189.47000	.00295	1.18182	2949.61
194.00000	.00898	1.18182	8979.05
194.58000	.00195	1.18182	1950.11
204.00000	.01449	1.18182	14488.16
204.58000	.00292	1.18182	2916.25
215.00000	.01679	1.90909	16792.58
216.00000	.01813	2.21212	18126.61
219.00000	.02212	2.51515	22122.65
221.00000	.02479	2.81818	24787.69

End of output file TM071797.DAT

Following are the two raw data sheets, as well as a graph of the measured and calculated CO₂ levels. Bitmap copies of the data sheets are contained in files DDSDATA1.PDF. The graph is contained in a Hewlett-Packard Graphics Language file TM071797.PDF.

①

CO2 Analyzer Test Data Sheet (Use New Sheet Each Day)

Analyzer Serial#: 135
 Cal Gas % CO2: 1.5 %
 Cal Gas Cylinder#: RL 105604
 Cal Gas Reading: 16,400 %
 Time checked: 1200
 Re-calibrated: Yes No

Date: 17 Jul 97
 Submarine: USS BATES
 SPHERE: TRUNK

Time	Pressure (fsw)	Depth of Water in Sphere (fsw)	Time of EVERY Vent	# of Divers	Diver Activity	CO2 (ppm) ANALYZER READING	Cylinder # (If take sample)
2122	0'	0'	0.71 : 46	2	REST	4650	—
2128	0	0	0.71 : 46			4346	—
2136	0	3'	0.33 : 20			3960	* 63
2143	0	3.5	0.63 : 41			6046	—
2151	0	5.5'	0.71 : 46			9220	—
2158	0	5.5'	0.65 : 39			7820	—
2205	0	5.5'	0.52 : 49			7066	—
2211	0	5.5'	0.75 : 47			6640	—
2219	0	5.5'	0.75 : 45			7280	44
2226	5'	5.5'	0.80 : 48			7660	—
2234	5'	5.5'	0.52 : 31			7680	—
2241	5'	5.5'	0.82 : 49			8200	—
2247	5'	5.5'	0.52 : 31			6140	—
2254	5'	5.5'	0.55 : 33			6420	—
2301	5'	5.5'	0.71 : 58			7000	—
2307	5'	5.5'	0.63 : 38			4580	—
2313	5'	5.5'	0.71 : 46			5240	—
2319	5'	5.5'	0.63 : 38	↓	↓	4806	—

Notes: * #63 APPEARED TO HAVE LESS VACUUM VOLUME THAN THE OTHER CYLINDERS AS PER TESTOR'S PERSONAL OPINION -30-

2

CO2 Analyzer Test Data Sheet

(Use New Sheet Each Day)

Analyzer Serial#: 135
 Cal Gas % CO2: 1.5 %
 Cal Gas Cylinder#: BC105604
 Cal Gas Reading: 16.400 %
 Time checked: 1200
 Re-calibrated: Yes No

Date: 17 Jul 97
 Submarine: USS BATES

SPHERE: TRUNK

Time	Pressure (fsw)	Depth of Water in Sphere (fsw)	Time of EVERY Vent	# of Divers	Diver Activity	CO2 (ppm) ANALYZER READING	Cylinder # (If take sample)
2325	5'	5.5'	0.73 :44	2	REST	4840	—
2331	5'	5.5'	0.70 :42			6880	—
2338	5'	5.5'	0.92 :55			5900	—
2344	5'	5.5'	0.75 :45			3800	—
2352	5'	5.5'	1.05 1:03			5700	—
2358	5'	5.5'	0.67 :40			5200	—
0006	5'	5.5'	0.43 :26			7000	—
0012	6'	5.5'	0.65 :34			7400	—
0017	6'	5.5'	0.65 :38			4720	—
0024	6'	5.5'	0.58 :35			5840	—
0031	6'	5.5'	0.47 :28			5600	—
0036	6'	5.5'	0.56 :35			6000	—
0046	6'	5.5'	0.58 :35			5840	—
0107	30'	5.5'	PRESS			11380	15
0108	40'	5.5'	PRESS			13240	24
0111	50'	5.5'	PRESS			15160	14
0113	60'	5.5'	PRESS			17780	34
				∨	∨		

Notes:

FIGURE 1

