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DIGITAL COMPUTATION OF DECOMPRESSION
PROFILES

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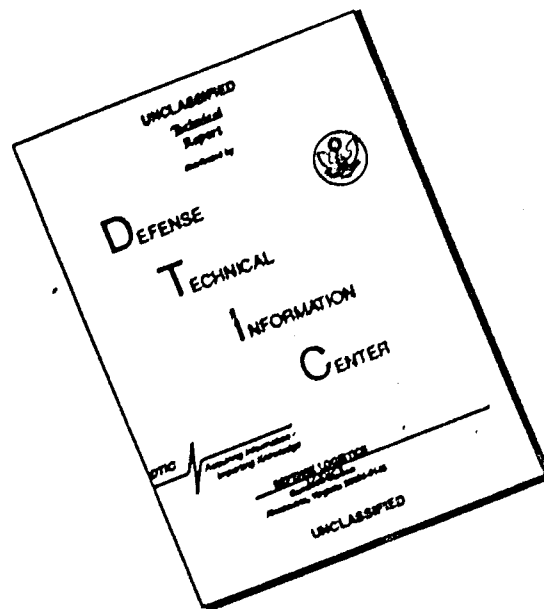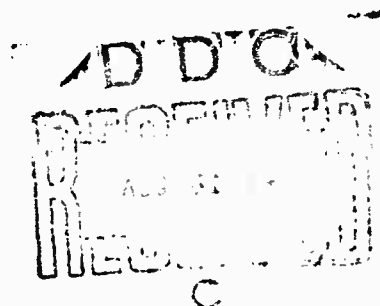
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DIGITAL COMPUTATION OF DECOMPRESSION PROFILES

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1a

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DCIEM REPORT NO. 884

DIGITAL COMPUTATION OF DECOMPRESSION PROFILES

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ABSTRACT

The Kidd-Stubbs pneumatic analogue decompression computer is used for the real-time prediction of the safe ascent depth following an excursion to depth. The theoretical model which is derived from the decompression computer can be solved using numerical techniques on a digital computer, or can be solved on an analogue computer. This report describes a series of Fortran IV programs which have been written to solve this theoretical model under a variety of conditions. The basic program can be used to calculate the safe ascent depth for a standard dive or for repetitive dives, and if desired, the safe ascent height for flying after diving. Modifications to the basic program are described which permit the use of the model for applications such as the design of pneumatic computers and the analysis of decompression tables. (U)

DIGITAL COMPUTATION OF DECOMPRESSION PROFILES

INTRODUCTION

The Kidd-Stubbs pneumatic decompression model,[1] consisting of four compartments connected in series by pneumatic resistance elements, is an analogue of the gas transfer characteristics of body tissues during compression and decompression. The equations of gas flow between compartments are non-linear and cannot be explicitly solved. However, they are amenable to solution by numerical analysis with a digital computer or by recourse to analogue computation with pneumatic or electronic devices. These techniques have been described in an earlier paper.[2]

THEORY

The absolute pressures in the four compartments of the theoretical model may be expressed by four non-linear first order differential equations describing gas dynamics in the 'slip-flow' regime:[1]

$$dP_j/dt = [\alpha_j (B_j + P_j + P_{j-1}) (P_{j-1} - P_j) \\ - \alpha_{j+1} (B_{j+1} + P_{j+1} + P_j) (P_j - P_{j+1})] /V_j \qquad \ldots \text{(1)}$$

where the number of the compartment is indicated by j (1,2,3 or 4), P_j, V_j are the absolute pressure and volume of the jth compartment, respectively, P_0 is the ambient or driving pressure (input to the model), α_j, B_j are flow constants of the jth resistor and $P_5 \equiv \alpha_5 \equiv B_5 \equiv 0$.

The constant α_j is defined by

$$\alpha_j = \alpha_j (Nd^4/L\eta)$$

where N is the number of pores in the resistor material

        L is the mean length of the porous sample in the direction of flow

        d is the mean pore diameter (assuming that the pores are of a circular cross-section)

and η is the viscosity of the gas.

The value of α_j may be determined by measuring the steady state gas flow through the pneumatic resistor and by recourse to the following equation:

$$\alpha_j = P_{fs} / T_{Aj} \Delta p_s (B_j + \Delta p_s + 2P_{fs})$$

where P_{fs} is the atmospheric pressure

        T_{Aj} is the time required for 1 cm³ of gas to flow through the resistor

and Δp_s is the 'driving' pressure, or pressure differential across the resistor causing the gas flow.

The flow constant B_j is defined by

$$B_j = B_j (\eta \sqrt{T/M} /d) \qquad \qquad \dots \ (4)$$

where   T is the absolute temperature of the gas

and   M is the molecular weight of the gas.

The pressure-time relation for transient flow of gas through a resistor-volume combination is

$$t = \frac{V}{\alpha (B + 2P_f)} \ \ln \left[\frac{(P_f - P_i)(B + P_f + P_c)}{(P_c - P_c)(B + P_f + P_i)} \right] \qquad \dots \ (5)$$

where α, B are flow constants of the resistor,

      V is the compartment volume,

      P_i is the initial compartment pressure at time $t = 0$,

      P_c is the compartment pressure at time t,

and P_f is the final compartment pressure.

The half-time, $T_{/2}$, of this combination is defined as the time required for the compartment pressure to decrease from a value of P_f to $(P_i + P_f)/2$ and can be expressed as

$$T_{1/2} = \frac{V}{\alpha (B + 2P_f)} \ \ln \left[\frac{2B + 3P_f + P_i}{B + P_f + P_i} \right] \qquad \dots \ (6)$$

For this decompression model, the half-time is specified for a compartmental pressure decrease from 50 psig to 25 psig. Table 1 shows values of α, B and $T_{1/2}$ for several gases and gas mixtures pertinent to a pneumatic resistor with a mean pore diameter of 0.125 μm for pressures in units of psi.

TABLE 1

Values of α, B and $T_{1/2}$ for several gases and gas mixtures pertinent to a pneumatic resistor with a mean pore diameter of 0.125μm.

Gas	M (amu)	$T_{1/2}$ (minutes)	V (c.c.)	α $\times 10^{-3}$	B
O_2	32	22.4	28.9	4.575	130.2
20/80 O_2/N_2	28.8	20.8	28.9	5.133	122.3
N_2	28	20.4	28.9	5.309	119.9
20/80 O_2/He	9.6	14.4	28.9	4.725	230.2
10/90 O_2/He	6.8	12.5	28.9	4.740	272.5

NUMERICAL ANALYSIS

Equation (1) consists of a set of first-order simultaneous differential equations of the form

$$dy/dx = f(x,y,z)$$

$$dz/dx = g(x,y,z)$$

where x is the independent variable and y and z are dependent variables. Such a system is amenable to numerical solution by a Runge-Kutta method. The technique used in this work is that due to Gill[3] characterized by the following set of equations, pertinent to the first dependent variable:

$$y_{n+1} = y_n + [k_{y1} + 2(1 - \sqrt{\tfrac{1}{2}})k_{y2} + 2(1 + \sqrt{\tfrac{1}{2}})k_{y3} + k_{y4}]/6 + 0(h^5) \qquad \dots \text{(7)}$$

where h = step size

$$k_{y1} = hf(x_n, y_n)$$

$$k_{y2} = hf(x_n + \tfrac{1}{2}h, y_n + \tfrac{1}{2}k_{y1})$$

$$k_{y3} = hf(x_n + \tfrac{1}{2}h, y_n + [-\tfrac{1}{2} + \sqrt{\tfrac{1}{2}}]k_{y1} + [1 - \sqrt{\tfrac{1}{2}}]k_{y2})$$

$$k_{y4} = hf(x_n + h, y_n - \sqrt{\tfrac{1}{2}}k_{y2} + [1 + \sqrt{\tfrac{1}{2}}]k_{y3}$$

This method is applied to the other dependent variables in a similar fashion.

After the four compartment pressures are calculated by the above method, the safe ascent depth for decompression is determined from the greatest of these pressures divided by a supersaturation ratio. Experimentally, it has been found that the human body can withstand some degree of supersaturation of inert gas without experiencing decompression sickness. The supersaturation ratio is defined by the equation

$$K_T = P_T/P_{SA} \qquad \dots \text{(8)}$$

where P_T is the greatest absolute compartment pressure

and P_{SA} is the pressure to which ascent may be made safely.

Experiments involving more than 4000 man-dives at DCIEM to depths as great as 300 ft of seawater have indicated that K_T can be expressed (for P_T in ft of seawater) as

$$K_T = 1.385/(1 - 13.7/P_T) \qquad \dots \text{(9)}$$

that is, as a function of the absolute pressure. Table 2 shows the relation between the supersaturation ratio and the greatest compartment pressure in this decompression model.

The safe ascent depth in gauge pressure, D_{SA}, can then be determined from

$$D_{SA} = \frac{P_T}{K_T} - P_A \qquad \dots \text{(10)}$$

where P_A is the barometric pressure at the water surface. The equation can be further simplified to

$$D_{SA} = \frac{P_T}{R} - P_{OFF} \qquad \dots \text{(11)}$$

4

where   R is a dimensionless decompression factor

and P_{OFF} is a pressure offset. Expressed in feet of seawater, the equation has the form (for $P_A = 33$ ft (abs.))

$$D_{SA} = \frac{P_T}{1.385} - 42.9 \qquad \qquad \ldots(11a)$$

TABLE 2

PRESSURE-DEPENDENT SUPERSATURATION RATIO

P_T ft seawater	$P_T - P_A$ ft seawater	D_{SA} ft seawater	K_T
33	0	-19.07	2.37
59.4	26.4	0	1.80
99	66	28.6	1.61
132	99	52.4	1.55
165	132	76.2	1.51
198	165	100.1	1.49
231	198	123.9	1.47
264	231	147.7	1.46
297	264	171.5	1.45
330	297	195.4	1.445
363	330	219.2	1.44

DIGITAL COMPUTER PROGRAMS

Several series of digital computer programs were written in FORTRAN IV for use on a PDP-9T computer at DCIEM. All programs utilize the same Runge-Kutta calculation method for determination of compartment pressures and the same safe ascent criterion.

IDENTICAL COMPARTMENT PROGRAMS

This series of programs concerns decompression models in which all compartments and pneumatic resistors are identical. The input and output data files are similar.

(a) Basic Decompression Program D6S:

(1) Options

The basic program in this series is D6S. It incorporates most of the features embodied in the five programs described in Reference 2 and operates within an 8K core of the PDP-9T. Appendix I contains the D6S source program which has several options that may be selected by a two digit integer called KEY at the beginning of the input data file:

(i) Standard Dive: KEY = 00

If KEY is any number other than 09 or those listed below, the diver's excursion depth is considered as a standard dive in which descent occurs at a constant rate, e.g., 60 ft/min, to the maximum depth. Upon leaving this depth after a specified time, the diver is considered to ascend at a constant rate to a depth from which his ascent is governed by the safe ascent criterion defined in equation (10). Programmed stops can be included in the descent to adequately represent a working diver's excursion to depth.

(ii) Impulse Dive: KEY = 04

This type of dive is used specifically for calibration of pneumatic decompression computers and consists of a step impulse of pressure applied to the model at time zero which is maintained for a duration time T at which the pressure is returned immediately to sea level. Compartment pressures are continuously calculated until sea level is reached.

(iii) Flying after Diving: KEY = 05

This is a standard dive in which calculations of compartment pressures are continued after the model has ascended to sea level with the provisos that the ambient pressure is maintained at sea level and the safe ascent 'depth' is expressed in terms of feet of altitude. This will be the height above sea level to which the model may safely ascend instantaneously at any time after surfacing.

(iv) Repetitive Dive: KEY = 10, 20, 30, . . .

The results of several excursions of the model to various depths can be obtained with this option of the D6S program. It consists of a standard dive in which the diver ascends to the surface via the safe ascent criterion with computation of safe ascent continuing for the duration of the diver's stay at the surface. Compartment pressures at the end of this time are used as initial conditions for the subsequent dive. The procedure is repeated N times, where N = KEY/10, finally finishing at sea level.

(v)   Repetitive Dive Followed by Flying after Diving: KEY = '5, 25, 35, . . .

This option is similar to that for repetitive diving with the difference that after the diver attains sea level on the last excursion to depth, the safe ascent applicable to his stay on the surface is expressed in feet of altitude above sea level and is pertinent to flying after repetitive diving.

(2) Input Data File Format

The input data file for the basic decompression program D6S is denoted as NLDIV SRC and must be loaded on the PDP-9T computer disc for operation of D6S. The following format must be used in the composition of this file:

line number	subject	format
1	KEY, TITL	I2, 14A5
2	A, B, R	E8.4, F5.1, F5.3
3	DTL, TMAX, PTOUT, RDES, RASC	5F4.1
4	T, G1, G	6F5.1
5	T, G1	
6	-T	
7	TTOP	
8	T, G1	
9	-T	
10	KEY, TITL	

The nature of the KEY symbol has been explained in the preceding section. TITL is any desired title comprising 70 or fewer alphanumeric characters. A is a flow constant of the pneumatic resistor related to α by the equation

$$A = \frac{\alpha}{V}$$

... (12)

and B is the flow constant defined earlier in this paper. R is the dimensionless computer constant required in the definition of the supersaturation ratio. The symbols DTL and TMAX denote the maximum step time in the Runge-Kutta computation technique expressed in minutes and the maximum length of the computer run, respectively. PTOUT is the printout interval, RDES is the descent rate and RASC is the ascent rate to the depth of safe ascent.

Line 4 represents the initial pressure-time state of the model where T is the initial time and G1 is the ambient pressure expressed in gauge units of feet of seawater. G represents an array containing the four initial compartment pressures which need not be equal to G1. If all are equal to G1, then there is no requirement for these values to be entered in the input file; they are established as equal to G1 by the program D6S.

Line 5 represents the point in the pressure-time profile at which the diver begins his ascent where T is the time for this event and G1 is the bottom gauge pressure. The program D6S calculates the pressure-time history of the model to this point assuming that the descent was made at a specified constant rate and that the diver remained at the bottom gauge pressure specified by G1 in line 5. If a stop or delay is desired during descent on a standard dive, the time that the diver leaves that stop and the gauge pressure of the stop can be inserted immediately before line 5 in the same format.

When a negative value is read as in line 6, computations for the ascent phase of the dive commence and continue until the diver attains sea level in the case of the standard dive or until 18 hours of altitude calculations are completed in the case of the flying after diving option.

Lines 7 through 9 are required only if the repetitive dive option is used. TTOP is the duration of time on the surface between the completion of one excursion and the commencement of another. T is the time that the diver commences his ascent to the surface from the bottom gauge pressure C1 as measured from the start of the current excursion. This sequence can be repeated for the number of dives required.

Computations pertinent to another independent dive can be initiated in the same input data file by entering a new KEY and TITL. When no more dive profiles are required, the input data file can be terminated by setting KEY equal to 09.

An example of the input data file for a standard dive with the "flying after diving" option is shown in Appendix 3.

(3) Output Data File Format

The output of the basic decompression program is presented in a file denoted as NLDIV LST. The format of the presentation consists of TITL, A, B, R, RASC, RDES and the following columns of data:

    (i)   the elapsed time of the dive,

    (ii)   the depth of the diver,

    (iii)   the altitude of safe ascent (if required),

    (iv)   the safe ascent depths in feet of seawater pertinent to each of the four compartments. Appendix 3 shows an example of the output file.

The basic decompression program presents output on the teletype or on the line printer when used in 8K core of the PDP-9T computer system. The peripheral assignments which must be made are

      for teletype A DKC1 3/TT 7.

      for line printer A DKC1 3/LP 7.

(4) Subprograms Required

One subprogram, EXIT, is required to operate the D6S basic decompression program.

(b) Abbreviated Basic Decompression Program D6SA:

The abbreviated basic program, D6SA, permits use of the teletype, the line printer, or the disk for the output file when utilizing 8K core of the PDP-9T computer system. The only difference from D6S is that altitude calculations are not performed. However, if the flying after diving option is required, the safe ascent gauge pressure values are presented. Consequently the output data file differs from that for D6S through the omission of an altitude column but the input data files are identical in format. Appendix 4 shows an example of the input and output files for an impulse dive using this program.

The peripheral assignments to be made to obtain the required output mode are the same as for D6S with the addition of

    disk output   A DKB0   1/DKB1 4, 3, 7.

The abbreviated program D6SA is not commonly used because the flying after diving option is rarely required and because there is greater flexibility in output mode.

(c) Basic Programs with Variable Descent M6S and M6SA:

These programs are basic decompression programs similar to D6S and D6SA respectively in which the rate of descent can be varied by specifying the pressure-time profile at closely space time intervals during the descent phase, e.g.

T	G1
0.0	0.0
0.1	6.0
0.2	12.0
0.3	18.0
0.4	30.0
0.5	40.0
0.6	50.0
.	.
.	.
.	.
.	.

This type of descent is a 'stepwise' approximation to a continuous pressure change but if the intervals in time are made very small, little error is made in the use of this approximation. Peripheral assignments for M6S and M6SA are the same as for D6S and D6SA respectively.

(d) Program for Analysis of Dive Tables D6ST:

The analysis of diving tables with the Kidd-Stubbs decompression model requires the determination of compartment pressures when the model is constrained to a 'step' decompression profile imposed by a diving table. The descent and ascent rates between steps on the decompression profile are established by RDES and RASC respectively. The input data file, NLDIV SRC, has the format:

```
KEY, TITL
A, B, R
DTL, TMAX, PTOUT, RDES, RASC
T, G1, G
T, G1    (Time at which pressure maximum is reduced)
T, G1    (Time at depth of first stop)
T, G1    (Time at depth of second stop)
  .
  .
  .
T, G1    (Time at depth of last stop)
-T
09
```

The time at which the pressure maximum is reduced includes the descent time but the duration at each stop does not include the ascent time between each stop. The program need not be terminated with KEY =09 so that repetitive diving tables may be analyzed. Peripheral assignments are the same as for D6SA.

Appendix 5 shows an example of a decompression table which has been analyzed with this program. If the safe ascent depth has not reached sea level at the termination of the last stop before surfacing (an unsafe decompression situation), the program continues to calculate the safe ascent depth until sea level is reached as shown in the example.

(e) Modified D6SA Programs:

(1) D6SAC2: This program is pertinent to operation of the Kidd-Stubbs decompression model with compensation for changes in atmospheric pressure. The computation process is based on gauge pressure units and a flow constant B', defined as

$$B' = B + 2P_A \qquad \dots (13)$$

where P_A is the barometric pressure.

P_A is inserted in the input data file, NLDIV SRC, immediately after RASC. The formula for safe ascent depth also incorporates changes in atmospheric pressure, viz

$$D_{SA} = \frac{P_g}{1.385} - 0.578\, P_A \qquad \dots (14)$$

where P_g is the gauge pressure of the controlling compartment.

(2) D6SMC: This program is a modification of the D6SA program that is applicable to a Kidd-Stubbs decompression model consisting of up to nine identical compartments. The number of compartments desired in any application of this program is entered into the input data file, NLDIV SRC, as a two-digit number immediately after R.

(3) D6SAT: A combination of D6SA and D6ST, this program is useful for comparison of a standard Kidd-Stubbs decompression model dive with a 'table' dive for the same hyperbaric exposure prior to ascent. It produces a series of comparisons for dives to the same depth but for different time exposures, e.g. 150 ft for 10, 20, 30 . . . minutes. The input data file, NLDIV SRC, has the following format pertinent to standard dives:

line number	subject	format
1	KEY, TITL	
2	A, B, R	
3	DTL, TMAX, PTOUT, RHS, RASC	
4	T, G1, G	
5	T_1, G1, KST	2F5.1, I2
6	-T	
7	KEY + 10, TITL	
8	T_2, G1, KST	
.	.	
.	.	
.	.	
.	.	

KST in line 5 is an integer. If it is zero then the program operates as either D6SA when KEY = 00 (pertaining to standard dives) or as D6ST when KEY = 01 (pertaining to diving tables). If KST is a positive integer, the program stores the computer compartment pressures at time T_1, for later use. When the dive is completed, KEY is read again and if it is 10 or 11, computation of compartment pressures resume at time T_1, using the stored values, and continue until time T_2 when the ascent phase of the new dive commences. This value of time and the compartment pressures are stored by the computer as starting conditions for the next dive. This process results in a considerable saving of computation time since the compartment pressures pertinent to the descent phase and exposure time at maximum pressure are calculated only once.

Termination of the series of dives is accomplished by setting $KEY = 09$ and initiation of a new series of dives occurs when $KEY = 00$ or 01. In the latter case, lines 2 through 4 of the input data file must be repeated. Output from this program is obtained either via line printer or via teletype utilizing 8K core of the PDP-9T computer system.

NON-IDENTICAL COMPARTMENT PROGRAMS

In the construction of pneumatic analogue decompression computers it is not possible to ensure that all compartments and pneumatic resistors are identical. A series of programs have been written to permit specification of the exact values of such parameters as A, B, V, and $T_{1/2}$ pertinent to each resistor-volume configuration. These programs are intended for validation of pneumatic analogue decompression computer performance.

(a) D6SVA   = The specification for each resistor-volume compartment is in terms of α, B and V.

(b) D6SVA1 = The specification of each resistor-volume compartment is in terms of T_A, $T_{1/2}$ and B.

(c) D6SVA2 = The specification of each resistor-volume compartment is in terms of V, $T_{1/2}$ and B.

The input data file format for D6SVA is as follows:

line number	subject	format
1	KEY, TITL	I2, 14As
2	A(1), A(2), A(3), A(4)	4E8.4
3	B(1), B(2), B(3), B(4)	4F5.1
4	V(1), V(2), V(3), V(4)	4F5.2
5	R	F5.3
6	DTL, TMAX, PTOUT, RDES, RASC	5F5.1
7	T, G1, G	6F5.1
8	T, G1	
9	-T	
10	KEY, TITL	
.		
.		
.		

For the other two programs in this series, the input data format is the same with the appropriate changes in lines 2 through 4.

ON-LINE PROGRAM AT HYPERBARIC CHAMBER: DIVER

The basic decompression program concerning four identical compartments has been adapted for operation in real-time from the hyperbaric chamber and is shown in Appendix 2. The output voltage from a pressure transducer in the 300 ft hyperbaric chamber at DCIEM is transmitted as real-time digital information into the PDP-9T computer system via an analogue-to-digital converter. In operation of the DIVER program, pressure in the chamber is sampled every 10 seconds and calculation of compartment pressures is made with the Runge-Kutta routine.

A conversational mode is used to start this program, to input data via the teletype and to instruct the chamber computer operator as to the operation of the program. Output of the elapsed time in the dive, pressure in the chamber, safe ascent depth, the number of the controlling compartment and the pressures in each of the four compartments occurs every minute via teletype. If the pressure in the hyperbaric chamber is permitted to drop below the predicted safe ascent depth, the program prints out the word 'VIOLATION' on the teletype as a warning to the chamber controller. At the end of a dive the sampling of the pressure may be terminated by typing CONTROL P. Theoretical calculations are continued in computer time representative of 12 hours with printout corresponding to one hour intervals.

Two related versions of DIVER have been written. DIVER1 presents only such basic information an output to the chamber controller as elasped time, chamber pressure, safe ascent depth and the number of the controlling compartment. DIVER2 is a version that presents the output of DIVER1 on teletype and stores the real-time output from DIVER on DECTAPE.

In addition to the subprogram, EXIT, these programs require a monitor program, ADF4TS, which allows the use of the analogue-to-digital converter.

ACKNOWLEDGMENT

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```
C           FILE D6S - BASIC 6S MODEL WITH RAMP DESCENT
C                            (WITH ALTITUDE CALCULATIONS)
C
            REAL INDATA (2),OUTDAT(2)
            LOGICAL FOUND,C,KTEST
            COMMON TITL(14),P(4),G(4),GBIG(4),AK(4,4),F(5)
            DATA INDATA(1),INDATA(2)/5HNLDIV,4H SRC/
            DATA OUTDAT(1),OUTDAT(2)/5HNLDIV,4H LST/
            DATA Z1,Z2,Z3/.207106781,.292893219,.707106781/
            DATA Z4,Z5,Z6/1.707106781,.585786433,3.414213562/
C
C     OPEN DATA FILE
C
            CALL SEEK (3,INDATA)
            CALL DLETE (7,OUTDAT,FOUND)
            CALL ENTER (7,OUTDAT)
1           READ (3,101) KEY, TITL
101         FORMAT (I2, 14A5)
            IF (KEY.NE.9) GO TO 2
            CALL CLOSE (3)
            CALL CLOSE (7)
            CALL EXIT
C
2           WRITE (7,102) TITL
102         FORMAT (1H1,14A5)
            READ(3,103) A,B,R
103         FORMAT(E8.4,F5.1,F5.3)
            READ(3,112) DTL,TMAX,PTOUT,RDES,RASC
112         FORMAT(5F4.1)
            WRITE (7,108) A, B, R, DTL
108         FORMAT(1H0,4X4HA = ,F9.8,5X4HB = ,F5.1,5X4HR = ,F5.3/
           1 1H0,3X16HMAX STEP TIME = ,F4.2,4H MIN)
            IF (KEY.EQ.4) GO TO 125
            WRITE (7,120) RASC,RDES
120         FORMAT(4X5HASC =F5.1,7H FT/MIN6X6HDESC =F5.1,7H FT/MIN/)
125         KTEST=5*(KEY/5).EQ.KEY
            TMAX1=TMAX
            WRITE (7,109)
109         FORMAT(1H0,51H TOTAL DIVE    ACTUAL    ALTITUDE
           1 6X35HSAFE ASCENT DEPTHS (FT OF SEAWATER)/2X10HTIME (MIN)
           2 21H DEPTH (FT) (1000 FT)9X1H1,8X1H2,8X1H3,8X1H4/)
            DTI=DTL*.1
C
C     INITIAL TIME AND PRESSURES
C
6           READ (3,104) T, G1,G
104         FORMAT (6F5.1)
            K = 1
            FOUND=G(1).EQ.0.
            DO 7 I=1,4
            IF (FOUND) G(I)=G1
            P(I) = G(I) + 33.
            W=GBIG(I) = P(I)/R-42.9
7           IF (GBIG(K).LT.W) K=I
```

```
            P1 = G1 + 33.
            PBIGK=GBIG(K) + 33.
            TT = T
            C=.FALSE.
            NS3=5
            GO TO 30
C
25          PMIN = 0.
            KPT=0
C
C    READ IN STEP TIME AND PRESSURES
C
11          DT = DTL
            PLAST = P1
            READ (3,104) T, G1
            IF (T.LT.0.) GO TO 12
            IF(NS2.EQ.2) T=T+TT
            NS2=1
            TL=T - .01
            IF (KEY.EQ.4) GO TO 59
            DP = .1*RDES
            W2=G1 + 33. - DP
56          IF (P1.LT.W2) GO TO 58
59          P1=G1+33.
            NS=5
            GO TO 57
58          DT=0.1
            NS=1
            P1=P1+DP
C
C    TEST FOR DESCENT PRESSURE AND TIME CHANGES
C
57          IF (P1.NE.PLAST) DT=DT1
19          IF (TT.LT.TL) GO TO 10
            IF((TTEST.LT..05).OR.(TTEST.GT.(PTOUT-.05)))GO TO 11
43          NS3=1
            GO TO 30
C
C    PART OF RUNGE-KUTTA ROUTINE
C
22          DO 14 I = 1,4
            W=GBIG(I) = P(I)/R-42.9
14          IF (GBIG(K).LT.W) K = I
            PBIGK=GBIG(K)+ 33.
            TT = TT + DT
            TTEST = AMOD (TT,PTOUT)
            W=.5*DT
            IF((TTEST.GT.W).AND.(TTEST.LE.(PTOUT-W))) GO TO 32
            IF (KPT.EQ.1) DT=DTL
            NS3=2
77          GO TO 30
32          IF((PBIGK.GT.PMIN).AND.(TT.LT.TMAX1))GO TO (56,10,18,17,57),NS
            NS3=3
            GO TO 30
```

```
C
C     TESTS FOR REPETITIVE AND FLYING AFTER DIVING
C
33          IF (KEY.GE.10) GO TO (23,26),NS2                    15
            IF (KEY.EQ.5) GO TO 20
            GO TO 1
C
12          PMIN = 33.
C
C     TEST FOR IMPULSE ASCENT
C
            IF (KEY.NE.4) GO TO 13
C
C     IMPULSE ASCENT
C
21          NS=2
24          P1=33.
            C = .FALSE.
            GO TO 10
C
C     STANDARD ASCENT TO FIRST STOP
C
13          DT = 0.1
            DP = 0.1*RASC
            NS=3
18          P1 = P1 -DP
            IF (P1.GT.PBIGK) GO TO 10
C
C     CONTINUOUS CONTROLLED ASCENT
C
            C = .TRUE.
            KPT = 1
            NS=NS3=4
            P1 = PBIGK
            GO TO 30
17          P1 = PBIGK
            GO TO 10
C
C     FLYING AFTER DIVING ROUTINE
C
20          KEY = 0
            TMAX1=TT+1080.
            PTOUT=15.0
            GO TO 41
C
C     REPETITIVE DIVING ROUTINE - SURFACE INTERVAL
C     W IS TIME AT SURFACE
C
23          READ (3,105) W
105         FORMAT (F5.1)
            TMAX1 = TT + W
            NS2=2
41          PMIN=0.
            GO TO 21
C
C     DESCENT AND DIVE REPETITION
C
26          TMAX1 = TMAX
            KEY = KEY - 10
            GO TO 25
```

```
C
C      OUTPUT PRINT ROUTINE
C
30             W=PBIGK
               IF ((KEY.EQ.4).OR.(T.GE.0.).OR.(.NOT.C)) W=P1
               GB=W-33.
38             WRITE (7,110) TT,GB,K,(GBIG(I),I=1,4)
110            FORMAT(3XF7.2,5XF6.2,14XI1,4(3XF6.2))
               IF (.NOT.KTEST) GO TO 44
               IF ((GBIG(K)+.0001).GE.0.) GO TO 44
               W=145.5300*(1.-(PBIGK/33.)**.1903)
               WRITE (7,115) W
115            FORMAT (1H+,25X,F5.2)
44             GO TO (11,32,33,10,25),NS3
C
C      RUNGE-KUTTA ROUTINE
C
10             J=1
               F(5)=0.
               X=P1
               DO 401 I=1,4
               Y=P(I)
               GO TO 450
401            CONTINUE
               GO TO 500
402            IF (C) X=X+AK(1,K)*.5
               DO 403 I=1,4
               Y=P(I)+AK(1,I)*.5
               GO TO 450
403            CONTINUE
               GO TO 500
404            IF (C) X=X+Z1*AK(1,K)+Z2*AK(2,K)
               DO 405 I=1,4
               Y=P(I)+Z1*AK(1,I)+Z2*AK(2,I)
               GO TO 450
405            CONTINUE
               GO TO 500
406            IF (C) X=X-Z3*AK(2,K)+Z4*AK(3,K)
               DO 407 I=1,4
               Y=P(I)-Z3*AK(2,I)+Z4*AK(3,I)
               GO TO 450
407            CONTINUE
               GO TO 500
408            DO 409 I=1,4
409            P(I)=P(I)+(AK(1,I)+Z5*AK(2,I)+Z6*AK(3,I)+
              1 AK(4,I))/6.
               GO TO 22
450            F(I)=A*(X-Y)*(B+X+Y)
               X=Y
               GO TO (401,403,405,407),J
500            DO 501 I=1,4
501            AK(J,I)=(F(I)-F(I+1))*DT
               X=P1
               J=J+1
               GO TO (10,402,404,406,408),J
               END
```

APPENDIX 2
ON-LINE PROGRAM FOR HYPERBARIC CHAMBER - DIVER

```
C        FILE DIVER, FOR ONLINE, REALTIME OPERATION AT HYPERBARIC
C        CHAMBER(OPERATOR VERSION WITH TELETYPE OUTPUT ONLY)
C        ALL DATA OUTPUT ON TELETYPE
C
         INTEGER ARG1,ARG2,ARG3
         COMMON P(4),GBIG(4),AK(4,4),F(5),TITL(8)
         DATA Z1,Z2,Z3/.207106781,.292893219,.707106781/
         DATA Z4,Z5,Z6/1.707106781,.585786438,3.414213562/
         DATA A1,B1,R/.00007912,274.5,1.385/
         DATA A2,B2/.00007281,516.7/
C
C        INSTRUCTIONS FOR OPERATOR
C
         WRITE(7,1)
1        FORMAT(/1X43HTYPE DIVE NO. AS DXXXX, DATE, BREATHING GAS)
         READ(4,8)TITL
8        FORMAT(8A5)
         WRITE(7,4)
4        FORMAT(/35H GAS MIX. TYPE 1 IF AIR, 2 IF O2-HE)
         READ(4,5)KEY
5        FORMAT(I1)
         WRITE(7,6)
6        FORMAT(/34H TYPE CHANNEL NO. AS 1, 2, 3, OR 4)
         READ(4,5)ARG1
C
C        SET INITIAL CONDITIONS
C
         IF(KEY.EQ.2) GO TO 90
         A=A1
         B=B1
         GO TO 95
90       A=A2
         B=B2
95       WRITE(7,18)
18       FORMAT(/18H BRING A/D ON LINE)
96       ARG3=1000
         CALL ADINIT(ARG1)
         CALL ADREAD(ARG1,ARG2,ARG3)
         CALL ADSTOP(ARG1)
         PA=FLOAT(ARG2)/2.
         WRITE(7,19)
19       FORMAT(/44H TURN A/D OFF-LINE, PRESS RETURN ON TELETYPE/)
         READ(4,28)
28       FORMAT()
         WRITE(7,9)TITL
9        FORMAT(//1X8A5/)
         WRITE(7,13)PA
13       FORMAT(5X13HATM. PRESS. =F5.1,9H FT(ABS.))
C
         WRITE (7,108) A, B, R
108      FORMAT(5X4HA = F9.8,5X4HB = F5.1,5X4HR = F5.3)
```

```
          WRITE (7,109)
109       FORMAT(//31H TOTAL DIVE    ACTUAL    SAFE ASC
         1 6X35HCOMPARTMENT DEPTHS (FT OF SEAWATER))
          WRITE(7,112)
112       FORMAT(32H TIME (MIN)  DEPTH(FT) DEPTH(FT)
         1 9X1H1,8X1H2,8X1H3,8X1H4/)
C
97        PTOUT=1.0
          P1=PA
          K=1
          DO 7 I=1,4
          P(I)=PA
7         GBIG(I)=-19.07
          NS1=NS2=NS3=1
          TT=0.
          GO TO 30
C
11        WRITE(7,29)
29        FORMAT(1X,10HSTART DIVE)
27        CALL ADINIT(ARG1)
C
C         START DIVE
C
          CALL CNTRLP
          GO TO 33
C
12        CALL ADREAD(ARG1,ARG2,ARG3)
          P1=FLOAT(ARG2)/2.
          DT=FLOAT(ARG3)/6000.
          GO TO 10
C
C         SELECTION OF DEEPEST COMPARTMENT AND TEST FOR PRINT
C
22        DO 14 I = 1,4
          W=GBIG(I)=(P(I)-PA-26.4)/R
14        IF (GBIG(K).LT.W) K = I
          TT = TT + DT
          TTEST = AMOD (TT,PTOUT)
          W=.5*DT
          IF((TTEST.GT.W).AND.(TTEST.LE.(PTOUT-W))) GO TO (12,10,38),NS2
          GO TO (15,48),NS1
15        NS3=2
46        GO TO 30
C
48        T=TT/60.
          GO TO 49
C
C         OUTPUT PRINT ROUTINE
C
30        T=TT
49        GK=GBIG(K)
          W=P1-PA
42        WRITE (7,110) T,W,GK,K,(GBIG(I),I=1,4)
110       FORMAT(2X,F6.1,5XF6.1,4XF6.1,4XI2,4(3XF6.1))
          IF(W.LT.GK) GO TO 31
44        GO TO (11,12,10,37,25),NS3
```

```fortran
C
31          WRITE(7,16)
16          FORMAT(1X9HVIOLATION/)
            GO TO 44
C
C           RUNGE-KUTTA ROUTINE
C
10          J=1
            F(5)=0.
            X=P1
            DO 401 I=1,4
            Y=P(I)
            GO TO 450
401         CONTINUE
            GO TO 500
402         DO 403 I=1,4
            Y=P(I)+AK(1,I)*.5
            GO TO 450
403         CONTINUE
            GO TO 500
404         DO 405 I=1,4
            Y=P(I)+Z1*AK(1,I)+Z2*AK(2,I)
            GO TO 450
405         CONTINUE
            GO TO 500
406         DO 407 I=1,4
            Y=P(I)-Z3*AK(2,I)+Z4*AK(3,I)
            GO TO 450
407         CONTINUE
            GO TO 500
408         DO 409 I=1,4
409         P(I)=P(I)+(AK(1,I)+Z5*AK(2,I)+Z6*AK(3,I)+AK(4,I))/6.
            GO TO 22
450         F(I)=A*(X-Y)*(B+X+Y)
            X=Y
            GO TO (401,403,405,407),J
500         DO 501 I=1,4
501         AK(J,I)=(F(I)-F(I+1))*DT
            X=P1
            J=J+1
            GO TO (10,402,404,406,408),J
C
C           END OF DIVE
C
33          CALL ADSTOP (ARG1)
            NS1=NS2=2
            NS3=5
            PA=P1
            W TE(7,17)
            CA _ CNTRLP
            GO  ^ 35
            GO TO 30
C
```

```
C               THEORETICAL CALCULATIONS FOR 12 HOURS AFTER DIVE
C
25              WRITE(7,13)PA
                WRITE(7,40)
40              FORMAT(12H END OF DIVE)
                NS3=4
                WRITE(7,41)
41              FORMAT(9X5HHOURS)
                GO TO 37
C
35              WRITE(7,17)
17              FORMAT(/)
                GO TO 97
C
37              DT=1.0
                PTOUT=60.
                NS2=NS3=3
                TMAX=TT+720.
                GO TO 10
C
38              IF(TT.GT.TMAX) CALL EXIT
                GO TO 10
                END
```

APPENDIX 3
EXAMPLE OF INPUT AND OUTPUT FILES FOR D6S PROGRAM

```
INPUT DATA FILE
05  STANDARD DIVE 200 FT FOR 10 MINUTES (FLYING OPTION)
.7912E-40274501385
0010999900020060006000
0030000000
0010002000
-1
09
```

```
OUTPUT FILE
 STANDARD DIVE 200 FT FOR 10 MINUTES (FLYING OPTION)
   A = .00007912     B = 274.5     R = 1.385
  MAX STEP TIME = 1.00 MIN
   ASC = 60.0 FT/MIN      DESC = 60.0 FT/MIN
```

TOTAL DIVE TIME (MIN)	ACTUAL DEPTH (FT)	ALTITUDE (1000 FT)		SAFE ASCENT DEPTHS (FT OF SEAWATER) 1	2	3	4
0.00	0.00	22.03	1	-19.07	-19.07	-19.07	-19.07
2.00	120.00	17.45	1	-16.14	-19.02	-19.07	-19.07
4.00	200.00	5.93	1	-6.53	-18.64	-19.06	-19.07
6.00	200.00		1	3.30	-17.70	-19.02	-19.07
8.00	200.00		1	12.96	-15.26	-18.92	-19.07
10.00	200.00		1	21.04	-14.42	-18.74	-19.05
12.00	80.00		1	23.65	-12.36	-18.47	-19.03
12.90	22.44		1	22.44	-11.50	-18.33	-19.02
14.00	20.38		1	20.38	-10.57	-18.13	-18.99
16.00	16.96		1	16.96	-9.20	-17.73	-18.94
18.00	13.92		1	13.92	-8.17	-17.31	-18.86
20.00	11.21		1	11.21	-7.41	-16.87	-18.77
22.00	8.77		1	8.77	-6.88	-16.44	-18.66
24.00	6.58		1	6.58	-6.53	-16.02	-18.53
26.00	4.58		1	4.58	-6.32	-15.63	-18.38
28.00	2.77		1	2.77	-6.24	-15.26	-18.23
30.00	1.11		1	1.11	-6.25	-14.92	-18.06
32.00	-0.41	0.35	1	-0.41	-6.33	-14.60	-17.88
32.00	-0.41	0.35	1	-0.41	-6.33	-14.60	-17.88
45.00	0.00	6.54	1	-7.08	-7.79	-13.27	-16.65
60.00	0.00	9.41	2	-11.01	-9.77	-12.75	-15.37
75.00	0.00	11.24	2	-13.19	-11.37	-12.75	-14.46
90.00	0.00	12.66	2	-14.51	-12.54	-12.95	-13.91
105.00	0.00	13.43	3	-15.37	-13.40	-13.20	-13.62
120.00	0.00	13.82	3	-15.95	-14.04	-13.47	-13.53
135.00	0.00	13.93	4	-16.36	-14.53	-13.73	-13.55
150.00	0.00	14.07	4	-16.66	-14.91	-13.99	-13.66
165.00	0.00	14.28	4	-16.89	-15.22	-14.23	-13.82
180.00	0.00	14.52	4	-17.07	-15.47	-14.46	-14.00
195.00	0.00	14.78	4	-17.21	-15.69	-14.69	-14.20
210.00	0.00	15.05	4	-17.33	-15.89	-14.90	-14.41
225.00	0.00	15.33	4	-17.44	-16.06	-15.10	-14.61

APPENDIX 4
EXAMPLE OF INPUT AND OUTPUT FILES FOR D6SA PROGRAM

INPUT DATA FILE
04 IMPULSE DIVE 200 FT FOR 30 MINUTES
.7912E-40274501385
00109999005006000600
0000000000
0030002000
-1
09

OUTPUT FILE
 IMPULSE DIVE 200 FT FOR 30 MINUTES
    A = .00007912   B = 274.5   R = 1.385
    MAX STEP TIME = 1.00 MIN

TOTAL DIVE TIME (MIN)	ACTUAL DEPTH (FT)	CRITICAL VOLUME	SAFE ASCENT DEPTHS (FT OF SEAWATER)			
			1	2	3	4
0.00	0.00	1	-19.07	-19.07	-19.07	-19.07
5.00	200.00	1	7.61	-17.20	-18.99	-19.07
10.00	200.00	1	27.63	-12.47	-13.51	-19.04
15.00	200.00	1	42.00	-6.11	-17.42	-13.91
20.00	200.00	1	52.44	0.39	-15.69	-18.61
25.00	200.00	1	60.17	7.88	-13.36	-18.09
30.00	200.00	1	66.03	14.49	-10.55	-17.29
35.00	0.00	1	45.53	17.89	-7.55	-16.20
40.00	0.00	1	32.16	17.78	-4.96	-14.85
45.00	0.00	1	22.90	16.20	-3.03	-13.37
50.00	0.00	1	16.17	14.09	-1.70	-11.85
55.00	0.00	2	11.10	11.88	-0.87	-10.39
60.00	0.00	2	7.17	9.75	-0.39	-9.02
65.00	0.00	2	4.04	7.78	-0.17	-7.80
70.00	0.00	2	1.51	6.00	-0.13	-6.72
75.00	0.00	2	-0.57	4.40	-0.21	-5.79
80.00	0.00	2	-2.31	2.97	-0.37	-5.02
85.00	0.00	2	-3.77	1.70	-0.57	-4.37
90.00	0.00	2	-5.01	0.56	-0.81	-3.85
93.00	0.00	2	-5.67	-0.05	-0.97	-3.59

EXAMPLE OF INPUT AND OUTPUT FILES FOR D6ST PROGRAM

INPUT DATA FILE   23
01 USN DIVE TABLE 150 FT FOR 30 MINUTES
.7912E-402741531385
0010999990020006000600
2000000000
0030001500
0003000200
0024000100
-1
09

OUTPUT FILE
USN DIVE TABLE 150 FT FOR 30 MINUTES
   A = .00007912   B = 274.50   R = 1.385
   MAX STEP TIME = 1.00 MIN
   ASC = 60.0 FT/MIN   DESC = 60.0 FT/MIN

TOTAL DIVE TIME (MIN)	ACTUAL DEPTH (FT)	CRITICAL VOLUME	SAFE ASCENT DEPTHS (FT OF SEAWATER)			
			1	2	3	4
0.00	0.00	1	-19.07	-19.07	-19.07	-19.07
2.00	120.00	1	-16.14	-19.02	-19.07	-19.07
4.00	150.00	1	-8.67	-18.67	-19.06	-19.07
6.00	150.00	1	-1.31	-17.96	-19.03	-19.07
8.00	150.00	1	4.30	-16.94	-18.95	-19.07
10.00	150.00	1	9.74	-15.67	-18.82	-19.06
12.00	150.00	1	14.57	-14.20	-18.63	-19.04
14.00	150.00	1	18.87	-12.53	-18.37	-19.01
16.00	150.00	1	22.63	-10.86	-18.05	-18.97
18.00	150.00	1	26.08	-9.05	-17.67	-18.91
20.00	150.00	1	29.12	-7.20	-17.22	-18.83
22.00	150.00	1	31.83	-5.33	-16.71	-18.74
24.00	150.00	1	34.26	-3.46	-16.13	-18.61
26.00	150.00	1	36.45	-1.60	-15.51	-18.46
28.00	150.00	1	38.43	0.23	-14.83	-18.29
30.00	150.00	1	40.23	2.02	-14.11	-18.07
32.00	30.00	1	38.05	3.66	-13.35	-17.35
34.00	20.00	1	33.08	4.84	-12.57	-17.59
36.00	20.00	1	28.86	5.53	-11.31	-17.29
38.00	20.00	1	25.26	6.00	-11.07	-16.97
40.00	20.00	1	22.17	6.13	-10.39	-16.63
40.20	20.00	1	21.89	6.19	-10.32	-16.60
42.00	10.00	1	19.15	6.17	-9.75	-16.27
44.00	10.00	1	16.43	6.00	-9.17	-15.90
46.00	10.00	1	14.14	5.72	-8.65	-15.51
48.00	10.00	1	12.03	5.36	-8.13	-15.12
50.00	10.00	1	10.26	4.95	-7.77	-14.72
52.00	10.00	1	8.64	4.50	-7.41	-14.32
54.00	10.00	1	7.19	4.02	-7.09	-13.92
56.00	10.00	1	5.89	3.54	-6.82	-13.53
58.00	10.00	1	4.72	3.05	-6.59	-13.15
60.00	10.00	1	3.66	2.57	-6.40	-12.77
62.00	10.00	1	2.70	2.09	-6.23	-12.41
64.00	10.00	1	1.83	1.62	-6.09	-12.06
64.40	10.00	1	1.66	1.53	-6.07	-11.99
66.40	0.00	2	0.50	1.07	-5.96	-11.65
68.40	0.00	2	-0.55	0.60	-5.87	-11.32
70.40	0.00	2	-1.51	0.14	-5.81	-11.01
71.40	0.00	2	-1.9.	-0.09	-5.78	-10.86