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IV. DWSD
Do., 07.07.2022:
deco workshop digital # IV

Über das DCIEM Modell

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Inhalt:

- Eine erster Überblick über Geschichte & Entwicklung
- Die XDC-X Serie (Cyberdiver)
- Das KS-1971 Modell
- Das DCIEM Modell 1983 [3]
- Das DCIEM Diving Manual 1992 [1] & [2]
- Die DCIEM Implementierung in Shearwater® Computern
- Lineare DCIEM Simulation mit DIVE Version 3_10
- (oder DIVE Version 3_11 [für Engländer …])
- Quellen und Links

- **Ein erster Überblick über Geschichte**
- **und Entwicklung:**

DCIEM, vormals:
Defence Research Medical Laboratory and
Institute of Aviation Medicine, dann:

DCIEM: Defence and Civil Institute of Environmental Medicine

aktuell:
DRDC: Defence Research and Development Canada;
https://www.drdc-rddc.gc.ca/

- **Ein erster Überblick über Geschichte**
- **und Entwicklung:**

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1962: D.J. Kidd & R.A. Stubbs; Dekorechnungen für Heliox-TG der kanadischen Navy, Ersatz für alte USN Tabelle
PADC: Pneumatic Analogue Decompression Computer
ca. 5.000 Test-TG mit Luft
1970: Mark VS: „Deko-Ei" mit 4 parallelen Kompartimenten
1971: KS-1971 Modell: 4 serielle Kompartimente, nicht-linear gekoppelt
Mitte-70iger: XDC-1, XDC-2, XDC-3; elektronische Computer
1979: Doppler-Messungen bei 500 Test-TG mit Heliox, Ziele, u.a.:
➔ Inkonsistenzen im KS-1971 Modell beheben
➔ Tabellen „sicherer" als USN Tabellen machen
➔ Multi-Level TG erlauben, ebenso wie: Bergsee, EAN, Sur-D
➔ Ergebnis [3]:

1983: USN Tabellen von 1979 werden durch die DCIEM AIR Diving Tabellen ersetzt [1].

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Die DCIEM HELIOX Tabellen für Hx16/84 werden von
Juni 1986 bis März 1991 getestet mit weiteren 1.471 TG
und realisieren eine P(DCS) = ca. 2 %;
und P(DCS) = ca. 4 % für außergewöhnliche Belastungen [2].

(Bemerkung:
Heliox ist *nicht* Bestandteil der Shearwater-Implementierung!)

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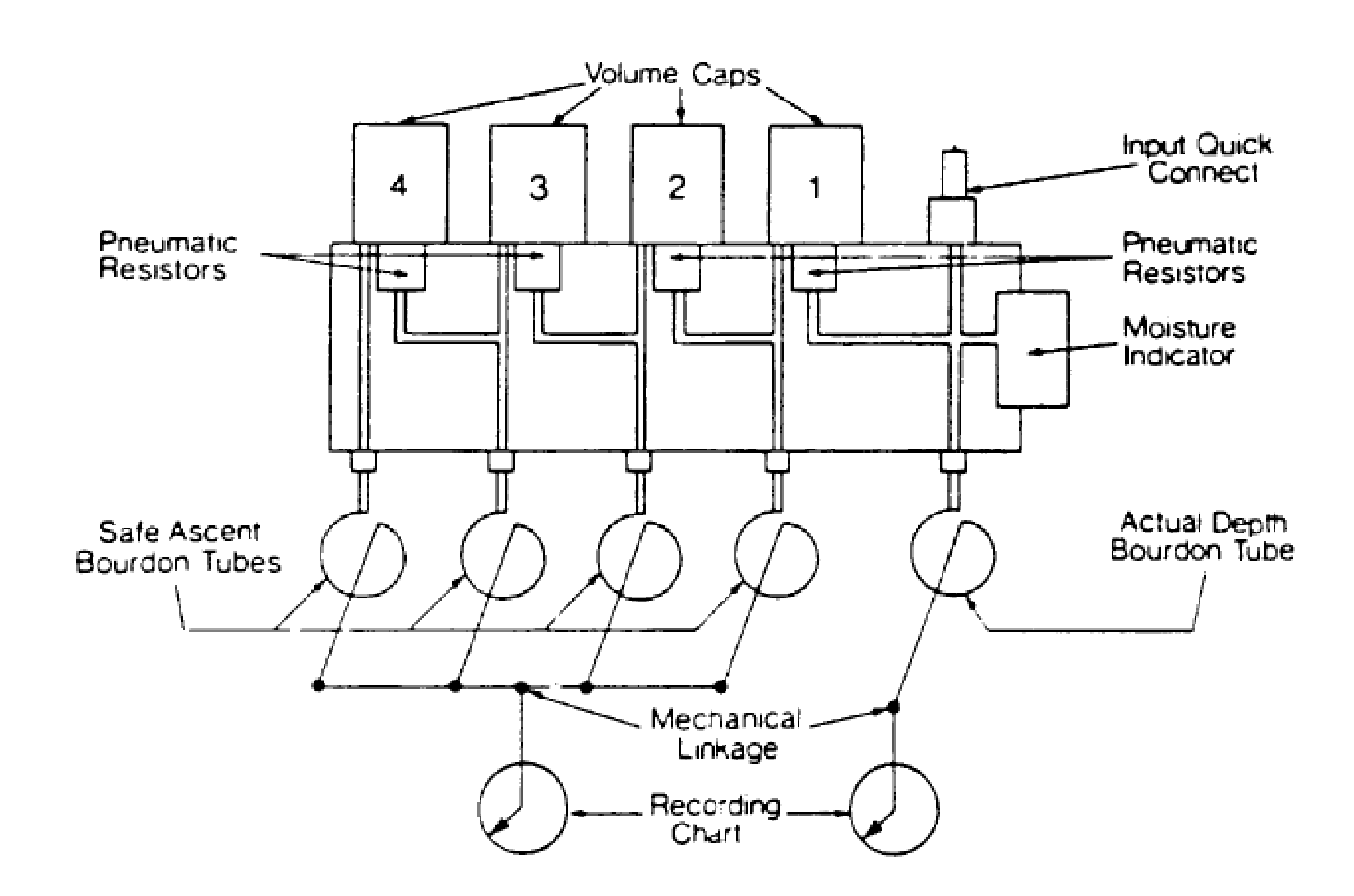

der PADC

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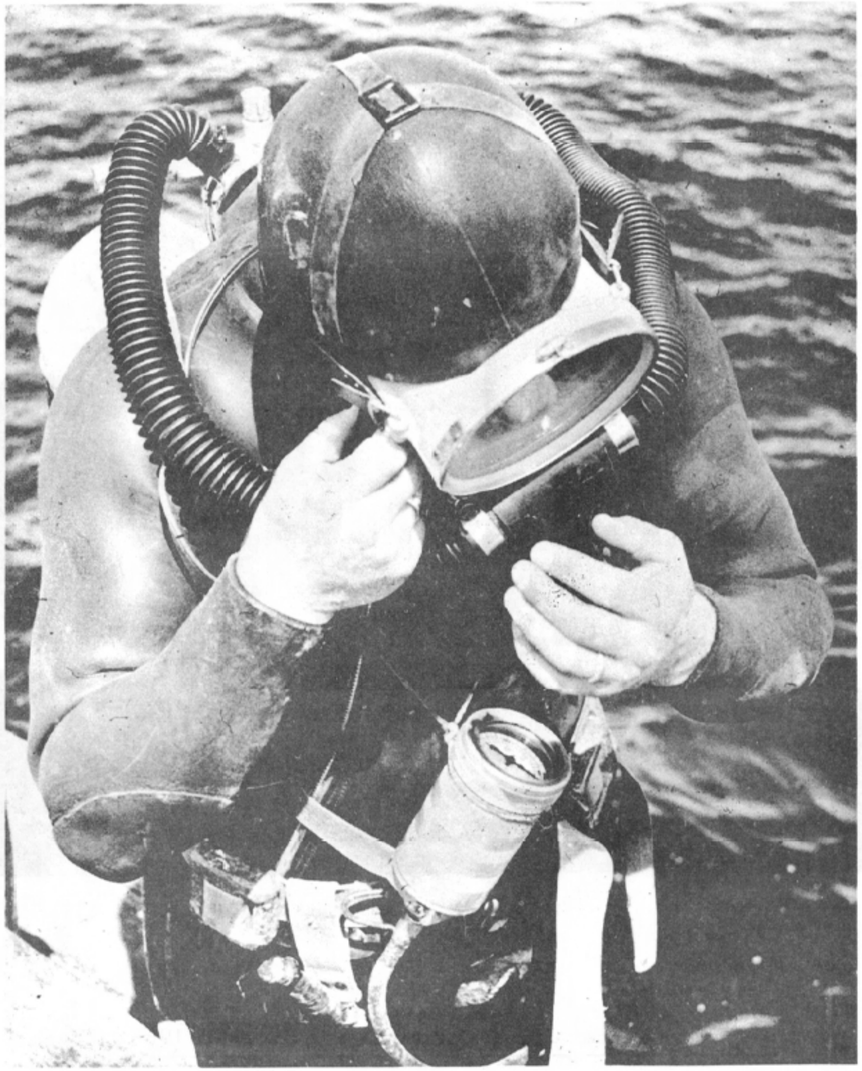

Fig. ix - Early sea diving with Model II P - Esquimalt, Jul. 63

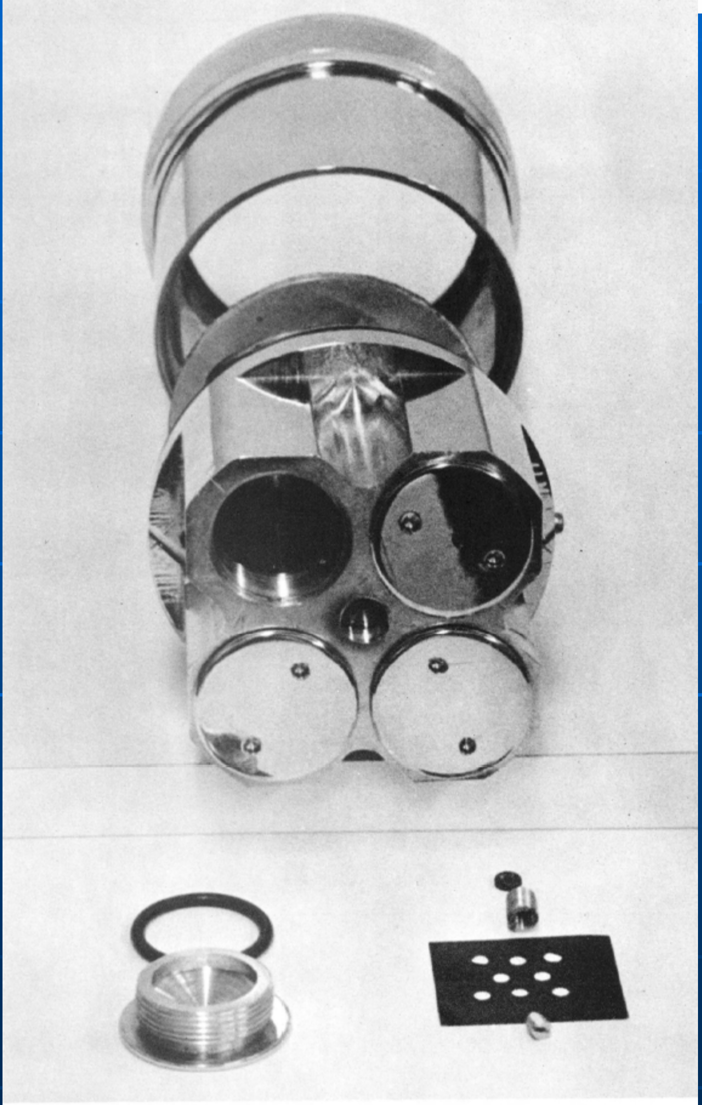

Fig vii. Operational Model Mark IV S

- Ein erste
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Fig. 16.6. Prototype Mk V S computer
With pressure case removed to show dial pointers and Bourdon tube assembly.

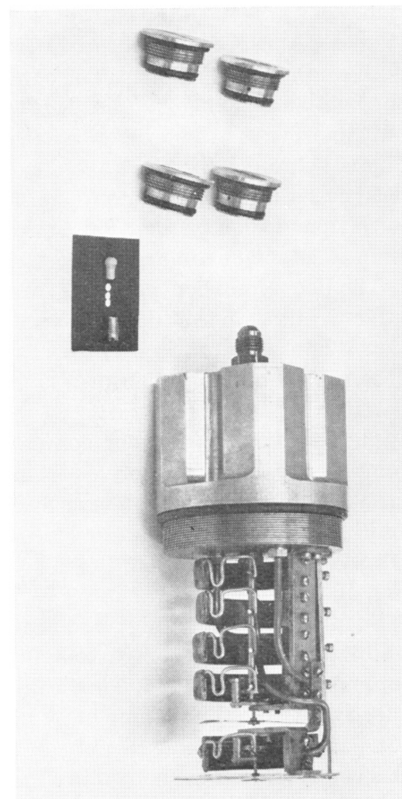

Fig. 16.7. Prototype Mk V S Computer
With volume plugs and a single pneumatic resistor disassembled.

Quelle: [250]

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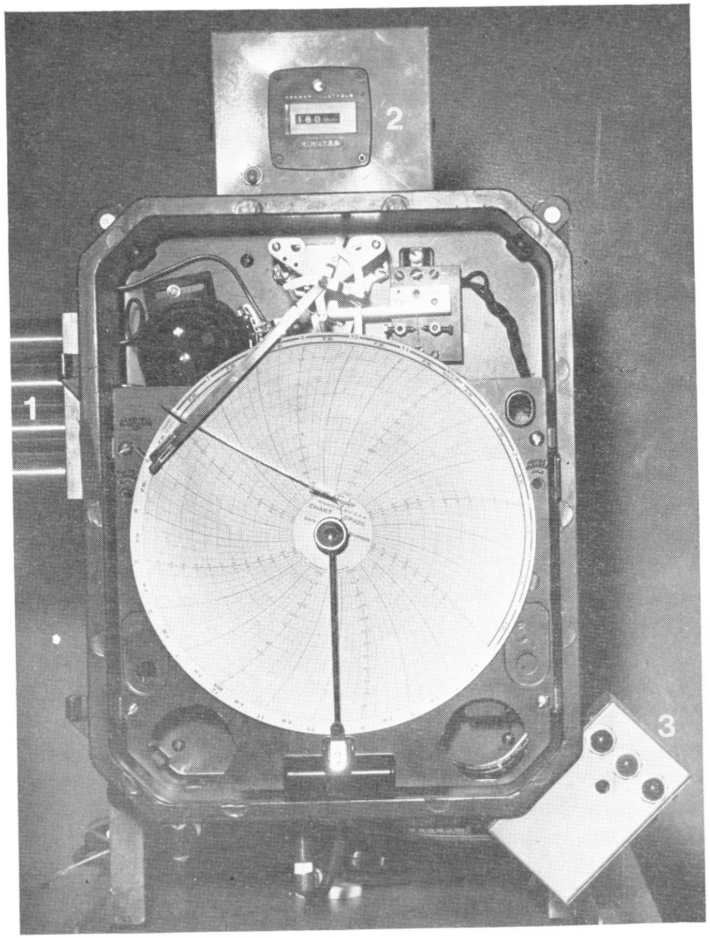

FIG. 16.12. Prototype Mark VI S pneumatic analogue computer

1. Four volume-resistor components connected in series.
2. Elapsed time clock.
3. Visual warning from error signal.

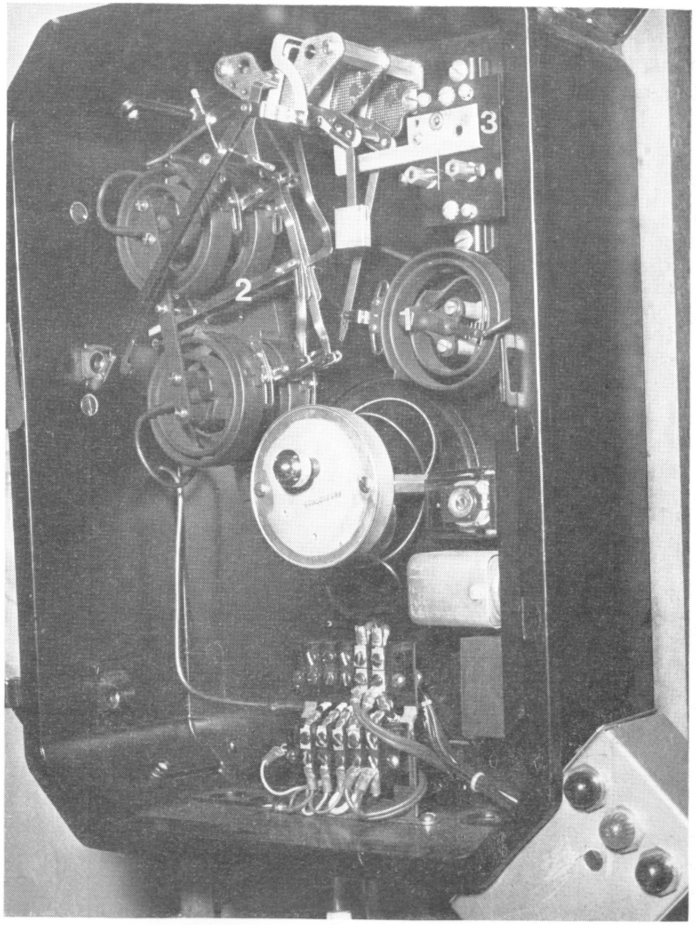

FIG. 16.13. Prototype Mark VI S pneumatic analogue computer, with chart plate removed

1. Ambient pressure Bourdon tube linked to first pen.
2. Four Bourdon tube assembly with pressure comparator linked to second pen.
3. Micro-switch giving error signal.

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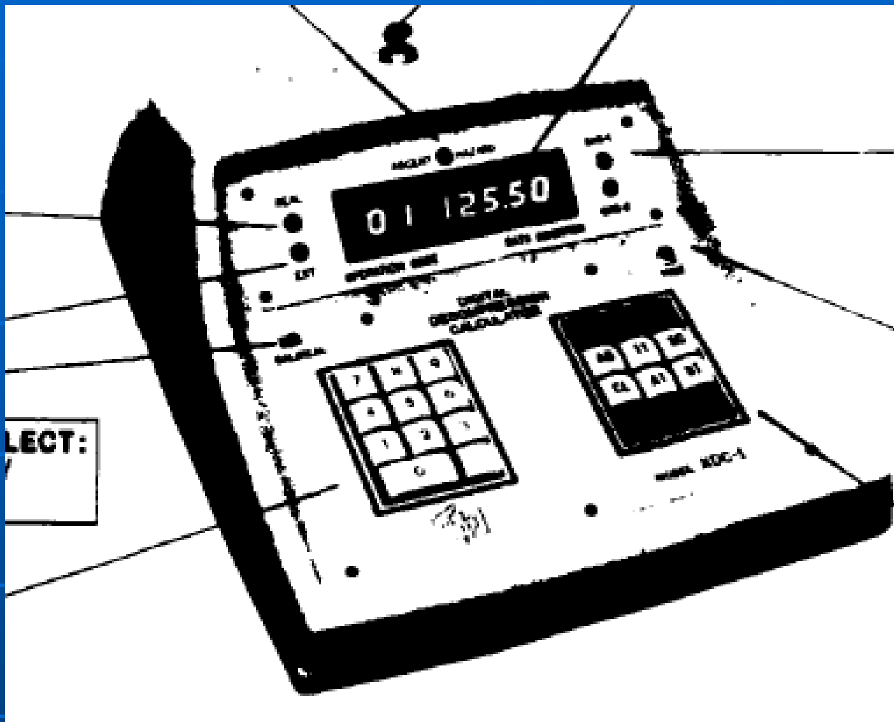

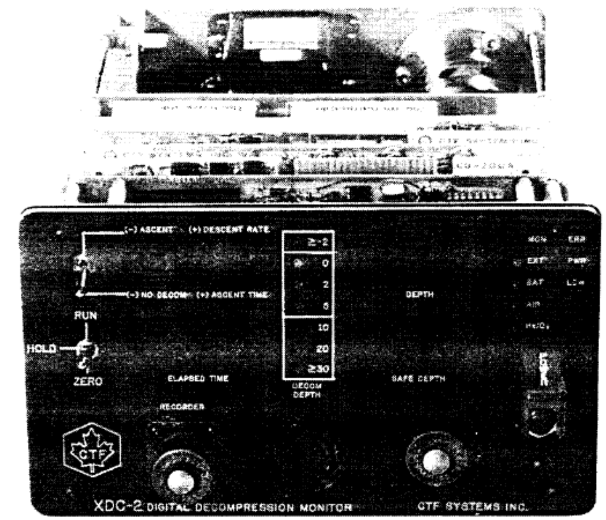

Fig. 3.8. XDC-2 Decompression Computer (from CTF Systems, Inc).

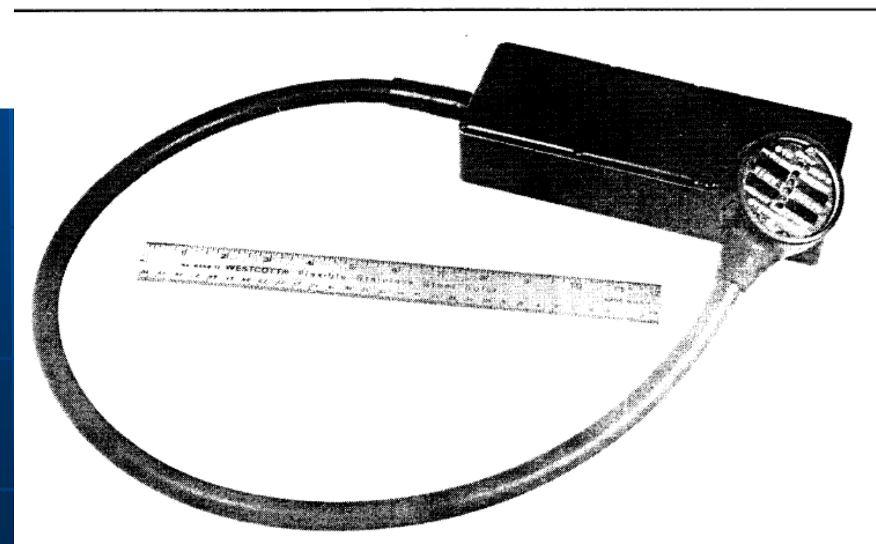

Fig. 3.9. XDC-3 Decompression Computer / Cyberdiver (from CTF Systems, Inc).

Die XDC Serie:

- 1: Tischrechner (oben ↑)
- 2: Steuereinheit für Deko-Kammern
- 3: Tauchcomputer

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- **und Entwicklung:**

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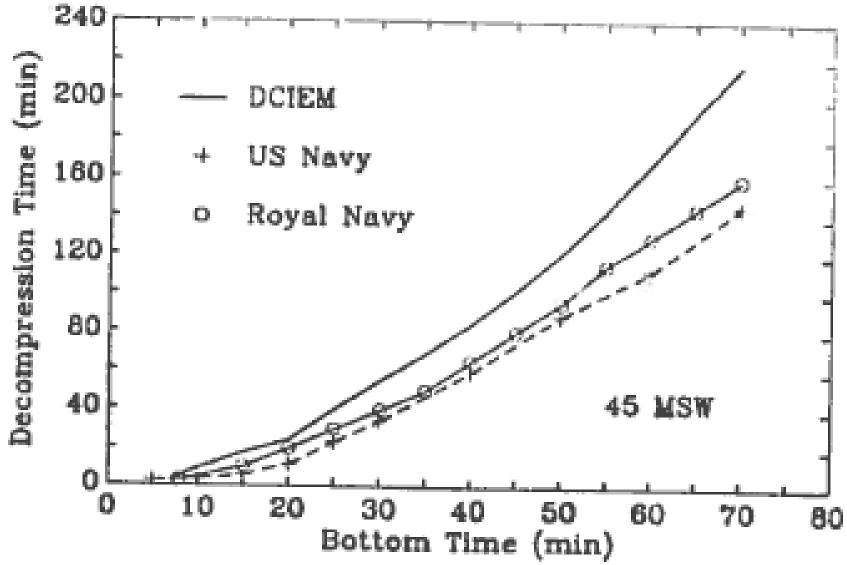

Figure 2. Comparison of Decompression Times

Depth (msw)	Bottom Time (min)	First Stop Depth (msw)		
		DCIEM	USN	RN
45	10	3	3	3
	15	6	3	6
	20	9	6	6
	30	12	6	9
	40	15	9	12
	60	18	12	15
	70	18	12	18
	80	18	15	21

Table 2. Comparison of first stop depths

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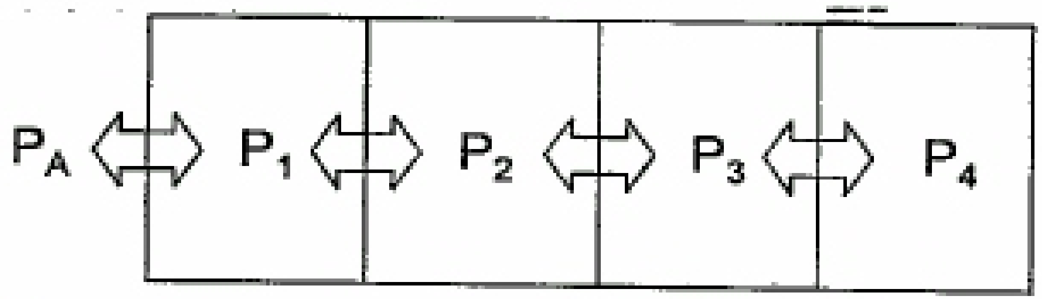
Das KS-1971 Modell:



$$\frac{dP_n}{dt} = A[(B + P_{n-1} + P_n)(P_{n-1} - P_n) - (B + P_n + P_{n+1})(P_n - P_{n+1})]$$

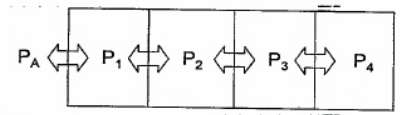
where $P_0 = P_A$ and $P_5 = 0$

Fig. 6. Serial compartments decompression model - Kidd-Stubbs Model (Canadian/ DCIEM).

4 Kompartimente, Diffusion, *seriell* geschaltet ← →
1 Kompartiment, Diffusion, BSAC/RNPL ← →
Parallele Schaltung, Perfusion:
zb.: Haldane (5), Workman (8), Bühlmann (16), …

• Das KS-1971 Modell:

Formeln (1):



$$\frac{dP_n}{dt} = A[(B + P_{n-1} + P_n)(P_{n-1} - P_n) - (B + P_n + P_{n+1})(P_n - P_{n+1})]$$

where $P_0 = P_A$ and $P_5 = 0$

Fig. 6. Serial compartments decompression model - Kidd-Stubbs Model (Canadian/ DCIEM).

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The operation of the PADC was described by the following set of four nonlinear differential equations (3):

$$dP_1/dt = A((B + P_0 + P_1)(P_0 - P_1) - (B + P_1 + P_2)(P_1 - P_2)) \quad (1)$$
$$dP_2/dt = A((B + P_1 + P_2)(P_1 - P_2) - (B + P_2 + P_3)(P_2 - P_3)) \quad (2)$$
$$dP_3/dt = A((B + P_2 + P_3)(P_2 - P_3) - (B + P_3 + P_4)(P_3 - P_4)) \quad (3)$$
$$dP_4/dt = A(B + P_3 + P_4)(P_3 - P_4) \quad (4)$$

where: P_i = the pressure in compartment i,
P_0 = the ambient pressure,
A = 0.0002596, gas flow constant (air, P in msw), and
B = 83.67, gas flow constant (air, P in msw).

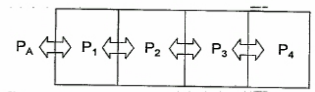
The safe ascent depth, SAD, was determined by:

$$SAD = P_t/1.8 - P_{s1}, \quad (5)$$

where P_t is the largest of the four compartments pressures and P_{s1} is the pressure at sea level (10.06 msw). This equation was the same for all four compartments. (All pressures in equations 1-5 are expressed as absolute gas pressures, not inert gas partial pressures).

Das KS-1971 Modell:

Formeln (2):



$$\frac{dP_n}{dt} = A[(B + P_{n-1} + P_n)(P_{n-1} - P_n) - (B + P_n + P_{n+1})(P_n - P_{n+1})]$$

where $P_0 = P_A$ and $P_5 = 0$

Fig. 6. Serial compartments decompression model - Kidd-Stubbs Model (Canadian/ DCIEM).

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$$SAD = P_t/R - OFF - P_{s1} \quad (6)$$

The two values, R = 1.385 and OFF = 3.018, gave a good fit to the SAD actually being used by the hyperbaric chamber operators.

The effect of the offset constant, OFF, was to make the supersaturation ratio depth-dependent, with the ratio becoming more conservative with increasing depth. The supersaturation ratio, "SR", can be obtained from Equation 6 as:

$$SR = P_t/(SAD + P_{s1}) = R/(1 - (R \times OFF)/P_t). \quad (7)$$

The surfacing ratio, given by

$$SR_o = P_t/P_{s1} \text{ (i.e., for SAD = 0)}, \quad (8)$$

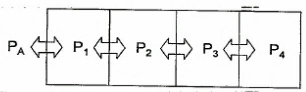
The final DCIEM 1983 model is thus derived from the KS-1971 four-compartment series model defined at the beginning of this paper with the following changes:

(1) First Compartment: R = 1.3, OFF = 4.8

(2) Second Compartment: R = 1.385, OFF = 2.5

(3) Third/Fourth Compartments: 1/R = 0.0, OFF = 0.0

• Das KS-1971 / DCIEM Modell:



$$\frac{dP_n}{dt} = A[(B + P_{n-1} + P_n)(P_{n-1} - P_n) - (B + P_n + P_{n+1})(P_n - P_{n+1})]$$

where $P_0 = P_A$ and $P_5 = 0$

Fig. 6. Serial compartments decompression model - Kidd-Stubbs Model (Canadian/

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Formeln (3):

This set of four first-order, nonlinear differential equations can only be solved by numerical techniques. The method used is the improved Euler method (Heun formula)

$$Y_{n+1} = Y_n + (Y_n' + f(x_n + h, Y_n + hY_n'))h/2$$

where $Y_n' = f(x_n, Y_n)$.

Once the four compartment pressures have been found, they are then scaled and offset by the supersaturation constants to obtain the safe ascent depth, D, for each compartment:

$$D = X_i P_i - Y_i - P_{atm}, \quad i = 1, 4,$$

where P_{atm} is the atmospheric pressure.

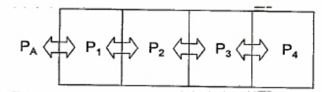
In the Kidd-Stubbs model, all the X's are set to 0.72202 and all the Y's are set to 9.9 fsw. The safe ascent depth for the complete model, D_{sa}, is the largest of the four compartment safe depths. The effect of the offset is to make the supersaturation ratio depth-dependent, with the ratio being more conservative at the deeper depths.

For the look-ahead calculations, the one-step Euler method is used to approximate the ascent and stage times:

$$Y_{n+1} = Y_n + hY_n'.$$

Numerische Lösung [4], p. 43 - 47

• Das KS-1971 / DCIEM Modell:



$$\frac{dP_n}{dt} = A[(B + P_{n-1} + P_n)(P_{n-1} - P_n) - (B + P_n + P_{n+1})(P_n - P_{n+1})]$$

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Formeln (4):

CALCULATIONS WITH OTHER GAS MIXTURES

In addition to the preprogrammed gases, compressed air and 20/80 oxygen-helium, other gas mixtures can be used by replacing the parameters in registers 17 to 22. These gas constants are functions of the molecular weight and the viscosity of the gas mixtures and can be found from the following relationships:

$$A = A_{air}\,\eta_{air}/\eta_{gas}, \text{ and}$$

$$B = B_{air}\left[\frac{\eta_{gas}}{\eta_{air}}\right]\left[\frac{M_{air}}{M_{gas}}\right]^{1/2},$$

where M is the molecular weight and η is the viscosity. The gas constant A is stored in registers 18 to 22 and the gas constant B is stored in register 17. For example, for a 20/80 oxygen-argon mixture, the gas constants are

$A = 66.48$ and
$B = 283.3$,

and for a 10/90 oxygen-helium gas mixture, they are

$A = 73.07$ and
$B = 611.7$.

The A and B constants will change the effective half-time of the compartments since the half-time of each individual compartment is given by

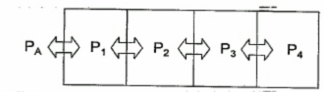
$$T_{1/2} = \frac{1}{A(B+2P_f)} \ln\left[2 - \frac{P_i - P_f}{B+P_i + P_f}\right]$$

where P_i and P_f are the initial and final pressures, respectively, (specifying where the half-time was measured). With a large value of B, such as for oxygen-helium, the half-time will be smaller than for a larger molecular weight gas; hence, the compartments will pressurize and eliminate gas much faster.

Anpassungen für Heliox [4], p. 43 - 47

- **Das KS-1971 / DCIEM Modell:**

Formeln (5):



$$\frac{dP_n}{dt} = A[(B + P_{n-1} + P_n)(P_{n-1} - P_n) - (B + P_n + P_{n+1})(P_n - P_{n+1})]$$

where $P_0 = P_A$ and $P_5 = 0$

Fig. 6. Serial compartments decompression model - Kidd-Stubbs Model (Canadian/DCIEM).

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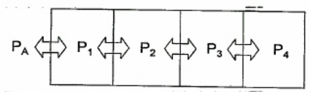
TABLE 1

Values of α, B and T½ for several gases and gas mixtures pertinent to a pneumatic resistor with a mean pore diameter of 0.125μm.

Gas	M (amu)	T½ (minutes)	V (c.c.)	α X10^{-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

• Das KS-1971 / DCIEM Modell:



$$\frac{dP_n}{dt} = A[(B + P_{n-1} + P_n)(P_{n-1} - P_n) - (B + P_n + P_{n+1})(P_n - P_{n+1})]$$

where $P_0 = P_A$ and $P_5 = 0$

Fig. 6. Serial compartments decompression model - Kidd-Stubbs Model (Canadian/ DCIEM).

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Formeln (6): Bsp. mit FORTRAN IV
Source Code für die Runge-Kutta Methode, Quelle: [5], p. 10

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:

$$y_{n+1} = y_n + [k_{y1} + 2(1 - \sqrt{½})k_{y2} + 2(1 + \sqrt{½})k_{y3} + k_{y4}]/6 + 0(h^5) \quad \ldots \quad (7)$$

where h = step size

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

$$k_{y2} = hf(x_n + ½h, y_n + ½k_{y1})$$

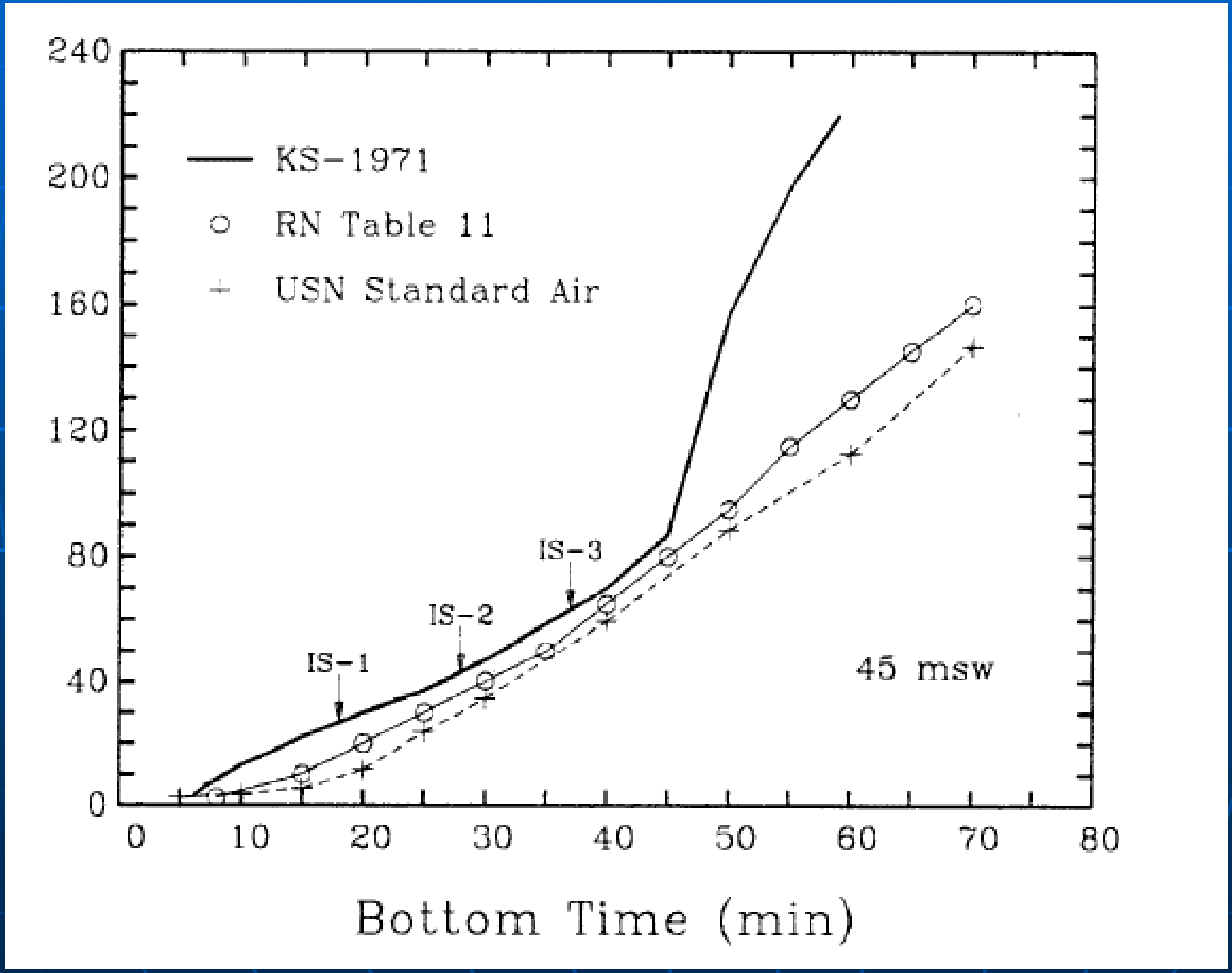
$$k_{y3} = hf(x_n + ½h, y_n + [-½ + \sqrt{½}]\, k_{y1} + [1 - \sqrt{½}]\, k_{y2})$$

$$k_{y4} = hf(x_n + h, y_n - \sqrt{½}\, k_{y2} + [1 + \sqrt{½}]\, k_{y3}$$

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

- **Das KS-1971 Modell:**

Besonderheiten:



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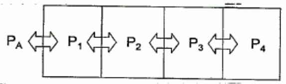


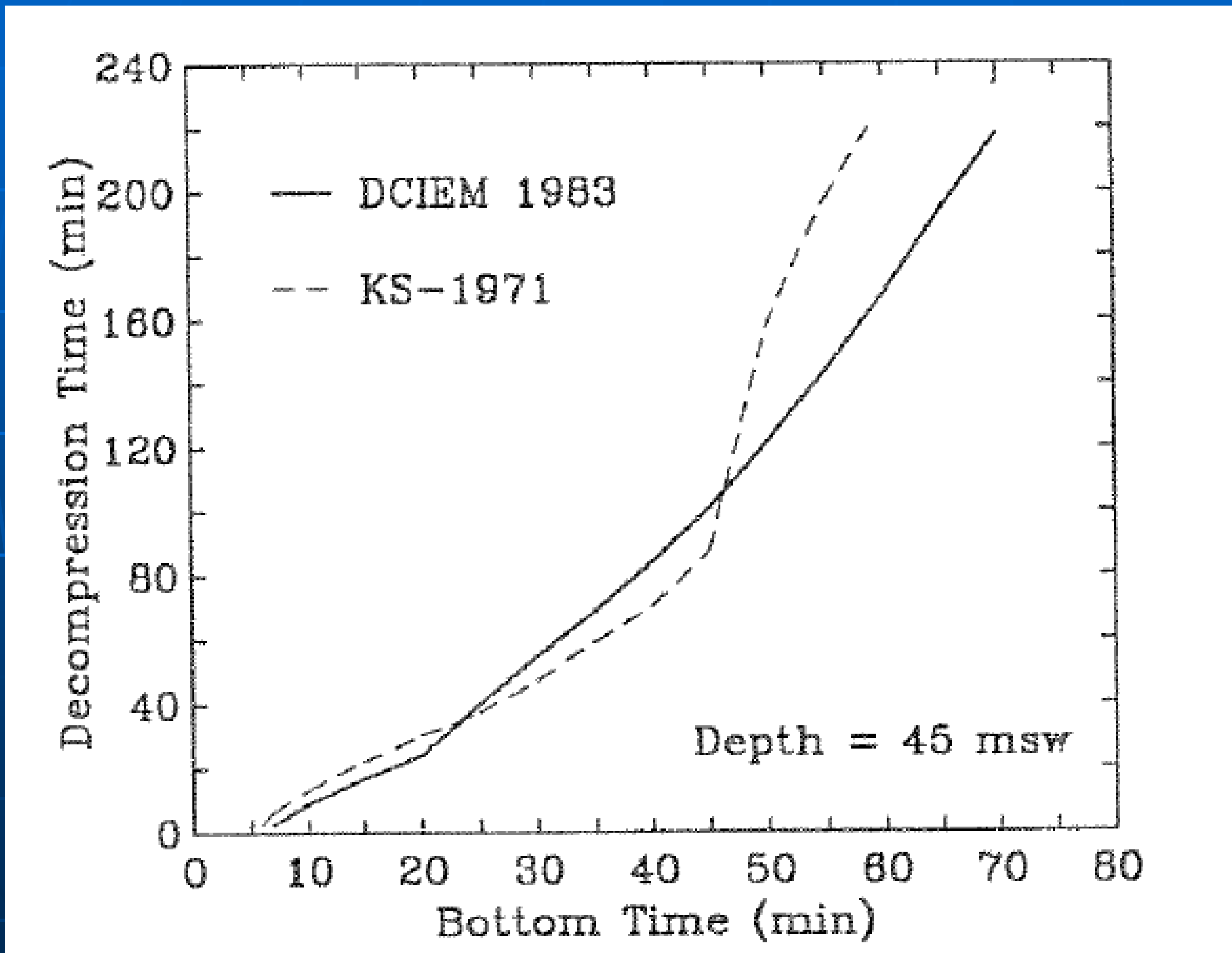
$$\frac{dP_n}{dt} = A[(B + P_{n-1} + P_n)(P_{n-1} - P_n) - (B + P_n + P_{n+1})(P_n - P_{n+1})]$$

where $P_0 = P_A$ and $P_5 = 0$

Fig. 6. Serial compartments decompression model - Kidd-Stubbs Model (Canadian/ DCIEM).

- # Das KS-1971 Modell:

Besonderheiten:



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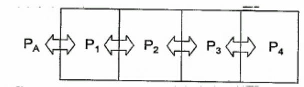


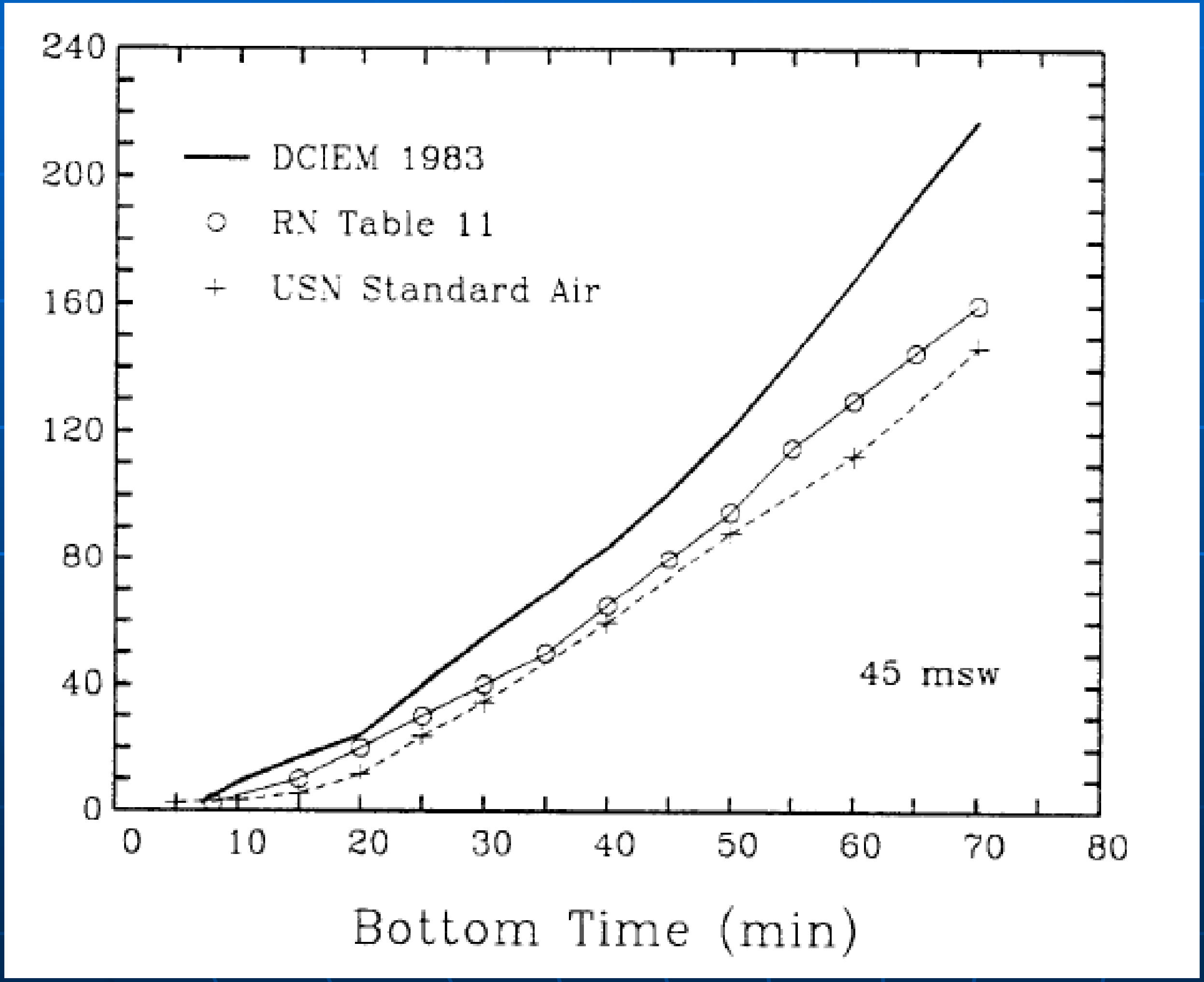
$$\frac{dP_n}{dt} = A[(B + P_{n-1} + P_n)(P_{n-1} - P_n) - (B + P_n + P_{n+1})(P_n - P_{n+1})]$$

where $P_0 = P_A$ and $P_5 = 0$

Fig. 6. Serial compartments decompression model - Kidd-Stubbs Model (Canadian/ DCIEM).

- **Das KS-1971 Modell:**

Vergleich:
DCIEM, Royal Navy (RN) und United States Navy (USN)



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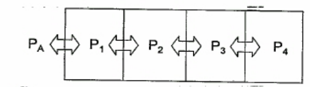
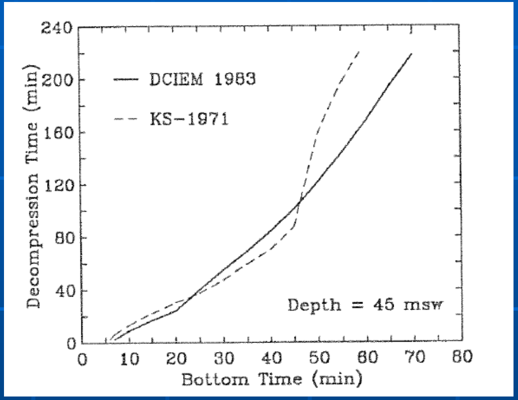


$$\frac{dP_n}{dt} = A[(B + P_{n-1} + P_n)(P_{n-1} - P_n) - (B + P_n + P_{n+1})(P_n - P_{n+1})]$$

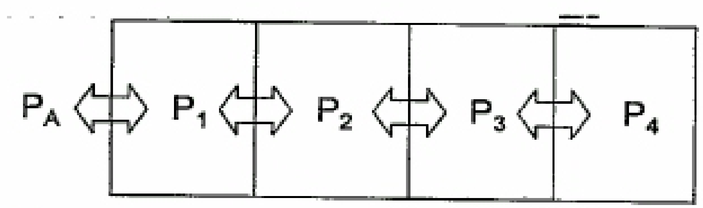
where $P_0 = P_A$ and $P_5 = 0$

Fig. 6. Serial compartments decompression model - Kidd-Stubbs Model (Canadian/ DCIEM).



Vergleich der Modelle (1):

DCIEM:	ZH-L 16 C:
Kidd-Stubbs 1971 model	Haldane/Workman/Schreiner
Diffusion $P_a \rightarrow P_{i,\ i = 1 \rightarrow 4}$	Perfusion
4 compartments	16 compartments
serial connections	parallel



$$\frac{dP_n}{dt} = A[(B + P_{n-1} + P_n)(P_{n-1} - P_n) - (B + P_n + P_{n+1})(P_n - P_{n+1})]$$

where $P_0 = P_A$ and $P_5 = 0$

Fig. 6. Serial compartments decompression model - Kidd-Stubbs Model (Canadian/ DCIEM).

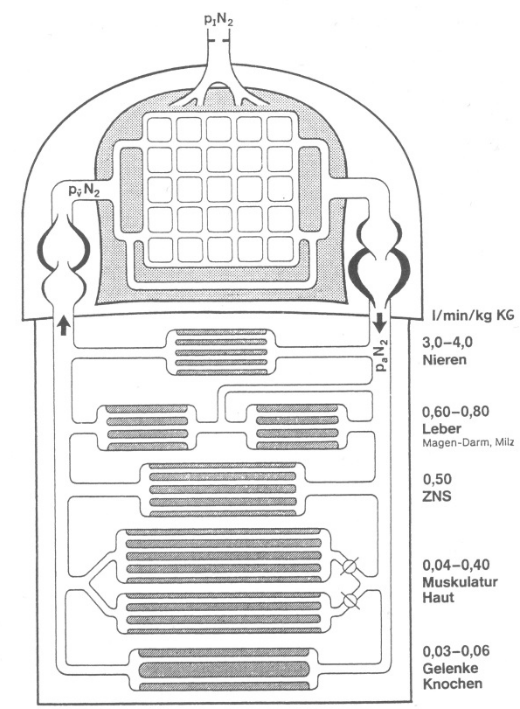


Abb. 15. Schematische Darstellung des Lungen- und Körperkreislaufs mit unterschiedlichen und variablen Durchblutungsanteilen der verschiedenen Organe

Vergleich der Modelle (2):

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DCIEM:	ZH-L 16 C:
1 half-time: 20.8 min for air, pressure dependant	16 half-times, fix, from ca. 4 → 635 min for air
4 free parameters	16 * 3 free parameters
4 (2) coupled ODE, non-linear (*)	1 linear ODE (Haldane equation)
solved numerically via: modified Euler or Runge-Kutta	analytic solution: simple exponential function
saturation / de-saturation: asymmetric	saturation / de-saturation: symmetric
safe ascent depth: linear equation	tolerated inertgas overpressure: linear equation
# test dives [3 → 5]: >> 7.500; Air + Heliox16, also: long bottom times, deep air, workload & cold water	# test dives [8], p.134: 1.311 air, 426 Heliox (p. 138); also: hypobaric & repetitive and saturation regime

ODE: ordinary differential equation

(*): only the first 2 compartments used for real table calculations

- **Die DCIEM Implementierung**
- **von Shearwater ® ,**
- **beispielsweise im PERDIX:**

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Vergleiche von NDL & run-times zwischen Manual & Tauchcomputer, alle Vergleiche & Details da:

Rosenblat M., Vered N., Eisenstein Y., Salm A. (22.02.2022)
On the reliability of dive computer generated run-times, Part IV;

DOI: 10.13140/RG.2.2.11469.72169

On the reliability of dive computer generated run-times, Part IV

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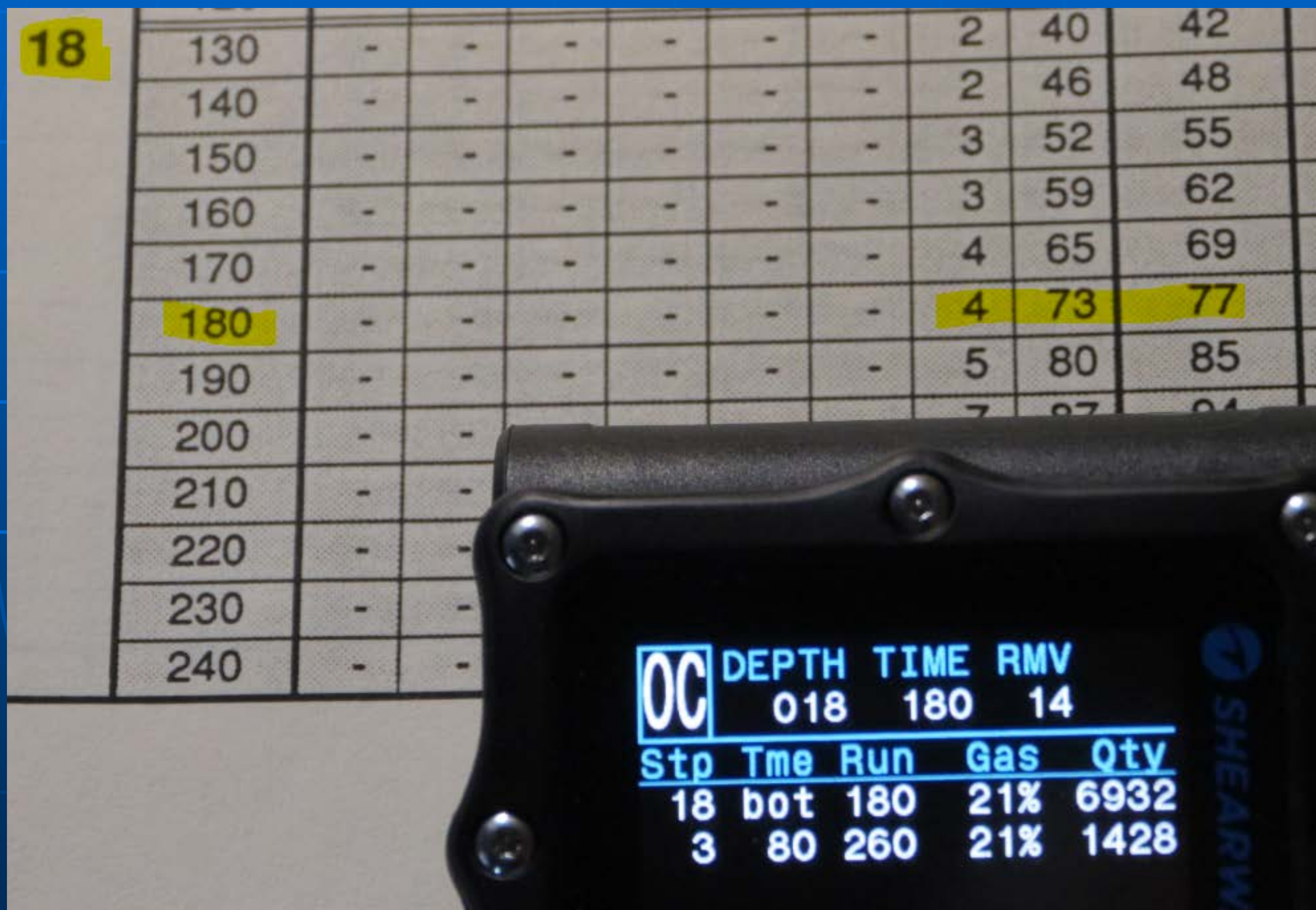
Results (3):

comparison of the schedule: 18 m, 180 min bottom time:



On the reliability of dive computer generated run-times, Part IV

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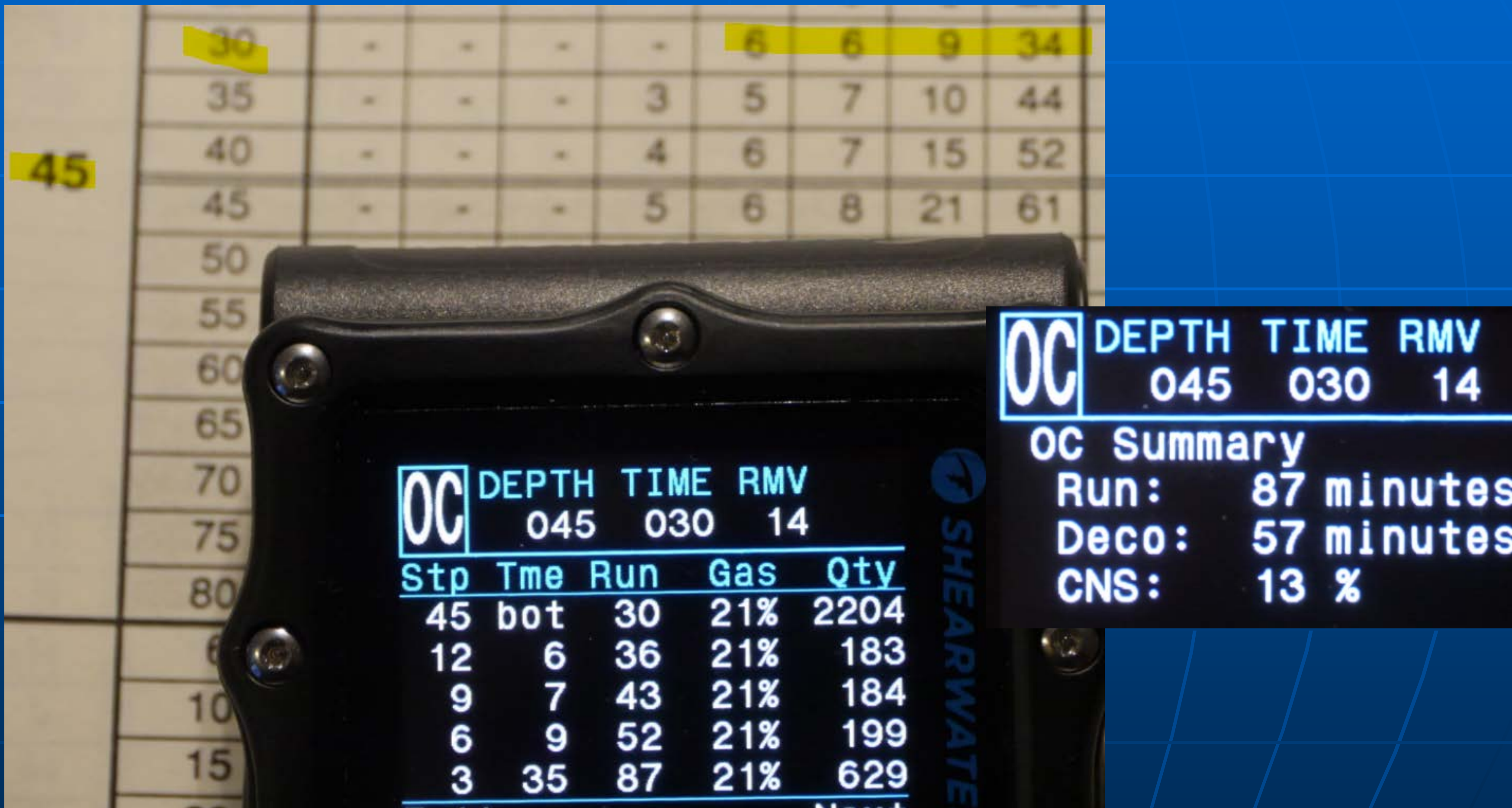
Results (9):

comparison of the schedule: 45 m, 30 min bottom time:



pls. cf. the attachment, slide # xx for another comparison of this schedule

For a comparison w. slide # yy, the 45 m/30‘ schedule, taken from: DIVING DECOMPRESSION COMPUTER (XDC-2) VALIDATION DIVES. 36 - 54 msw, F PHASE I – PRELIMINARY RESULTS, p. A-7, tested with 6 man-dives:

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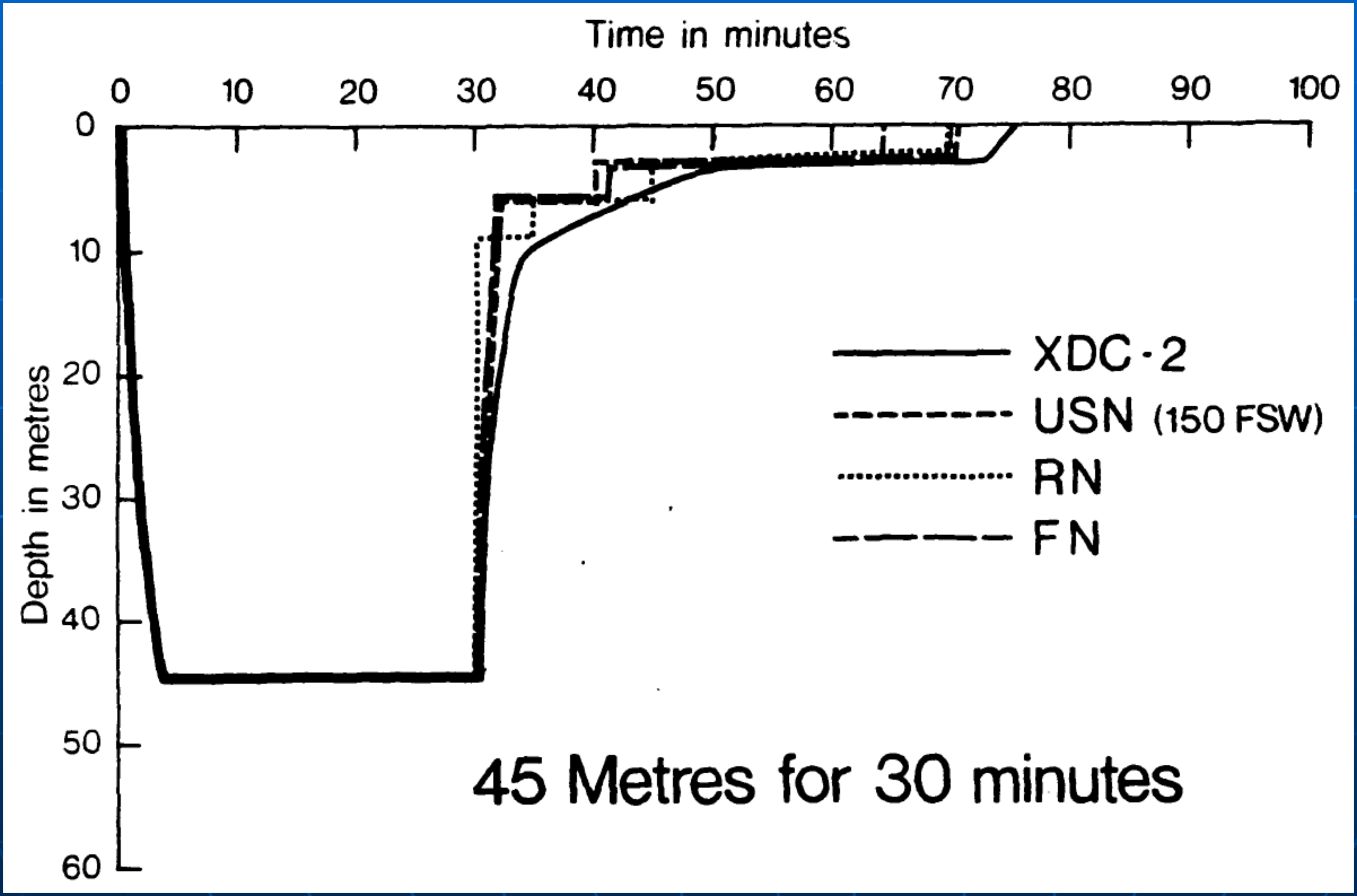

XDC-2: pneumatic dive computer
USN: United States Navy 1958,
RN: Royal Navy,
FN: French Navy;

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Abschliessende Einschätzung der Autoren:

Quelle: [3], S. 17:

The KS model, it must be realized, is a decompression calculation method rather than a decompression model, with the equations defining the model being derived from the operation of the pneumatic analogue decompression computer rather than from the physiology of decompression. Hills (20) makes the distinction clear between decompression calculation methods and decompression models. In a decompression calculation method, the equations and constants have been selected to fit the data. If the equations or constants prove inadequate, then other equations or constants are introduced until a good fit is achieved. Moreover, calculation methods are restricted to a limited range of conditions. It should be noted that most methods used for deriving decompression tables are calculation methods instead of mathematical models of decompression. These include the modified "Haldane" models which has been widely used for developing tables.

Abschliessende Einschätzung der Autoren:

Quelle: [3], S. 17, und weiterhin:

Hempleman (11) has indicated that a precise knowledge of the aetiology of decompression sickness is not a necessary prerequisite for successful decompression table calculations. Hence, it is not necessary to have a "physiological" model to calculate decompression tables. The important factor is that the model or method is based on actual diving data and predicts safe decompression. Selected profiles from DCIEM 1983 have been extensively tested for bottom times where the decompression requirements were reduced and for bottom times where the decompression requirements were extended in comparison to the KS-1971 model. The results showed that the DCIEM 1983 tables are as safe as the KS-1971 tables for short, moderate dives and much safer for dives in the KS IS 2/3 region. At extended bottom times where the 'tail' of the KS-1971 model has been reduced, the DCIEM 1983 model also gave excellent results.

- **Eine DCIEM „Implementierung“**
- **= lineare Simulation mit DIVE V3_10 / 11:**

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Vergleiche von run-times von Box-Profilen mit maximaler Bottom time, mit Luft, zwischen Manual &
DIVE Version 3_10 bzw. 3_11: alle Vergleiche & Details da:

Rosenblat M., Vered N., Eisenstein Y., Salm A. (04/2022)
The mapping of the DCIEM Air-diving table to a standard Haldane- / Workman- / Schreiner - algorithm

DOI:10.13140/RG.2.2.27420.36480

- **Bergseetauchen**

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Vergleiche von run-times mit dem Box-Profil 42 m / 25 min für den Galileo G2, Aladin TEC 2G & Ratio iX3m mit ZH-86 und Shearwater Perdix mit DCIEM für ca. 0,8 Bar / ca. 2.000 über N.N.:

Rosenblat M., Vered N., Eisenstein Y., Salm A. (07/2022)
On the reliability of dive computer generated run-times: Part VII: Altitude Test

DOI: 10.13140/RG.2.2.14589.64487

- **Bergseetauchen**

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Ergebnisse:

Synopsis of results for 42 m / 25 min @ 2.100 → 2.399 m above SL:

RATIO iX3M DEEP	TTS = 20 min (*)
ZH-86 table 42 m / 24'	TTS = 36 min
ZH-86 table 42 m / 27'	TTS = 44 min
Scubapro ALADIN TEC 2G @ MB Level = 0:	TTS = 48 min
Scubapro Galileo „G2"@ MB Level = 0:	TTS = 53 min
PERDIX with DCIEM option	TTS = 60 min
DCIEM table 54 m / 25'	TTS = 70 min

MB Level (= Micro Bubble Level) are proprietary modifications of the tolerated compartment inertgaspressures, here they are set = 0. This implies that the original ZH-L16 C values should be used.

(*): despite the used Gradientfaktors, default: GF Hi = GF Lo = 0.93

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Das komplette DCIEM AIR Diving Manual:

Quelle: [1], die Luft-Tabelle, metrisch auf: S. 1B-5 → 1B-18;

i.e.: http://www.divetable.eu/p125936.pdf

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Quellen:

[1] DCIEM Diving Manual, DCIEM No. 86-R-35: Part 1 AIR Diving Tables and Procedures, Defence and Civil Institute of Environmental Medicine, Canada, March 1992

[2] DCIEM Diving Manual, DCIEM No. 92-50: Part 2 Helium-Oxygen Surface-Suppplied Decompression Procedures and Tables; Defence and Civil Institute of Environmental Medicine, Canada, October 1992

[3] Nishi R. Y., Lauckner G. R. (September 1984) Development of the DCIEM 1983 Decompression Model for compressed Air diving, DCIEM No. 84-R-44

[4] Nishi R. Y. (Oct. 1980) A user guide to the DCIEM XDC-1 digital decompression calculator, DCIEM-TC-80-C-58

[5] AD-765 704 DIGITAL COMPUTATION OF DECOMPRESSION PROFILES Ronald Y. Nishi, et al. Defence and Civil Institute of Environmental Medicine Downsview, Ontario January 1973

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Quellen:

The dive computer manufacturers homepage:
https://www.shearwater.com/

Der DCIEM flyer:
https://www.shearwater.com/wp-content/uploads/2021/07/DCIEM-Manual-Metric-Web-1.pdf