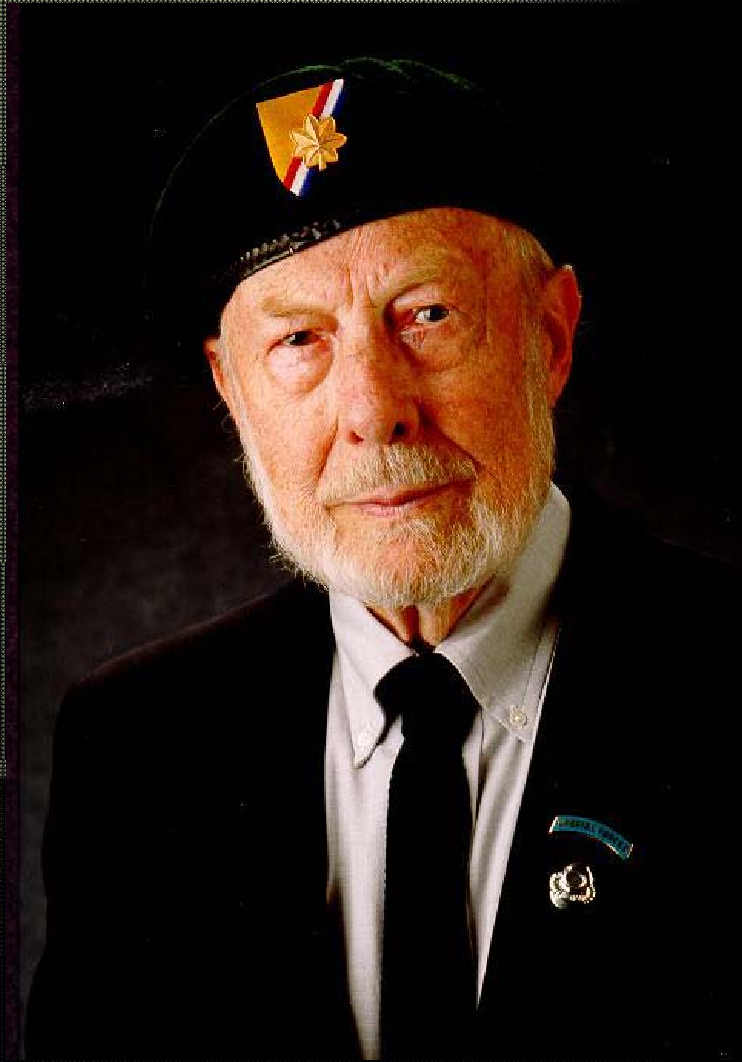
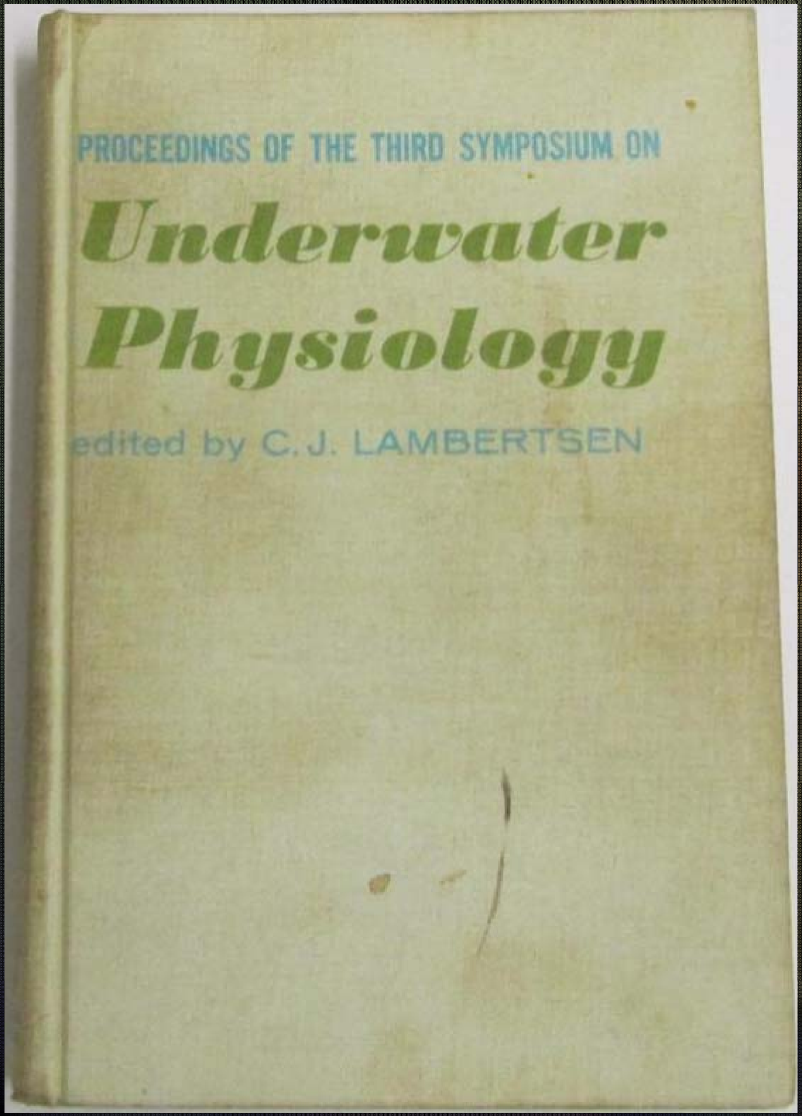
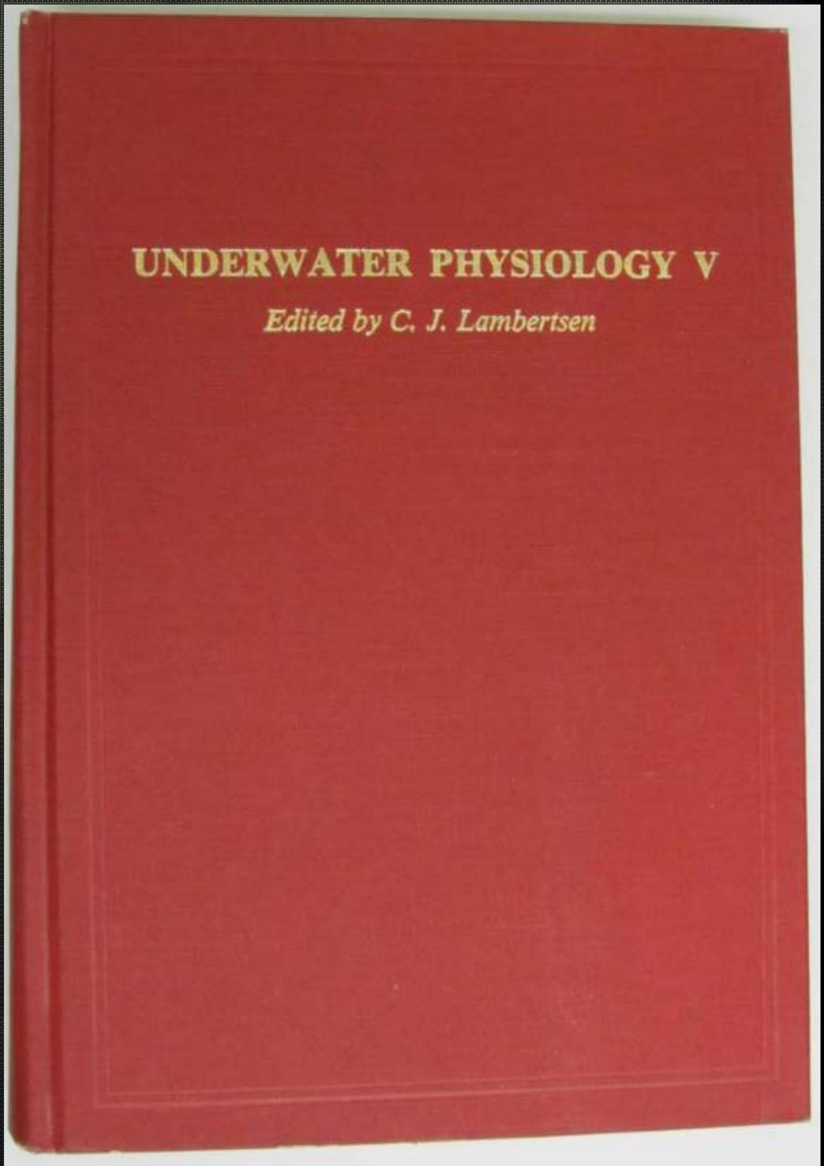
Tribute to the Extraordinary Life's Work of Dr. Christian .J. Lambertsen



Overview

- Introduction –Dr. Michael Gernhardt
- Military Contributions – Dr. Richard Vann
- Contributions to Oxygen and Respiratory Physiology – Dr. Jim Clark
- Contributions and Influences on Diving and Aerospace Physiology and Operations – Dr. Michael Gernhardt

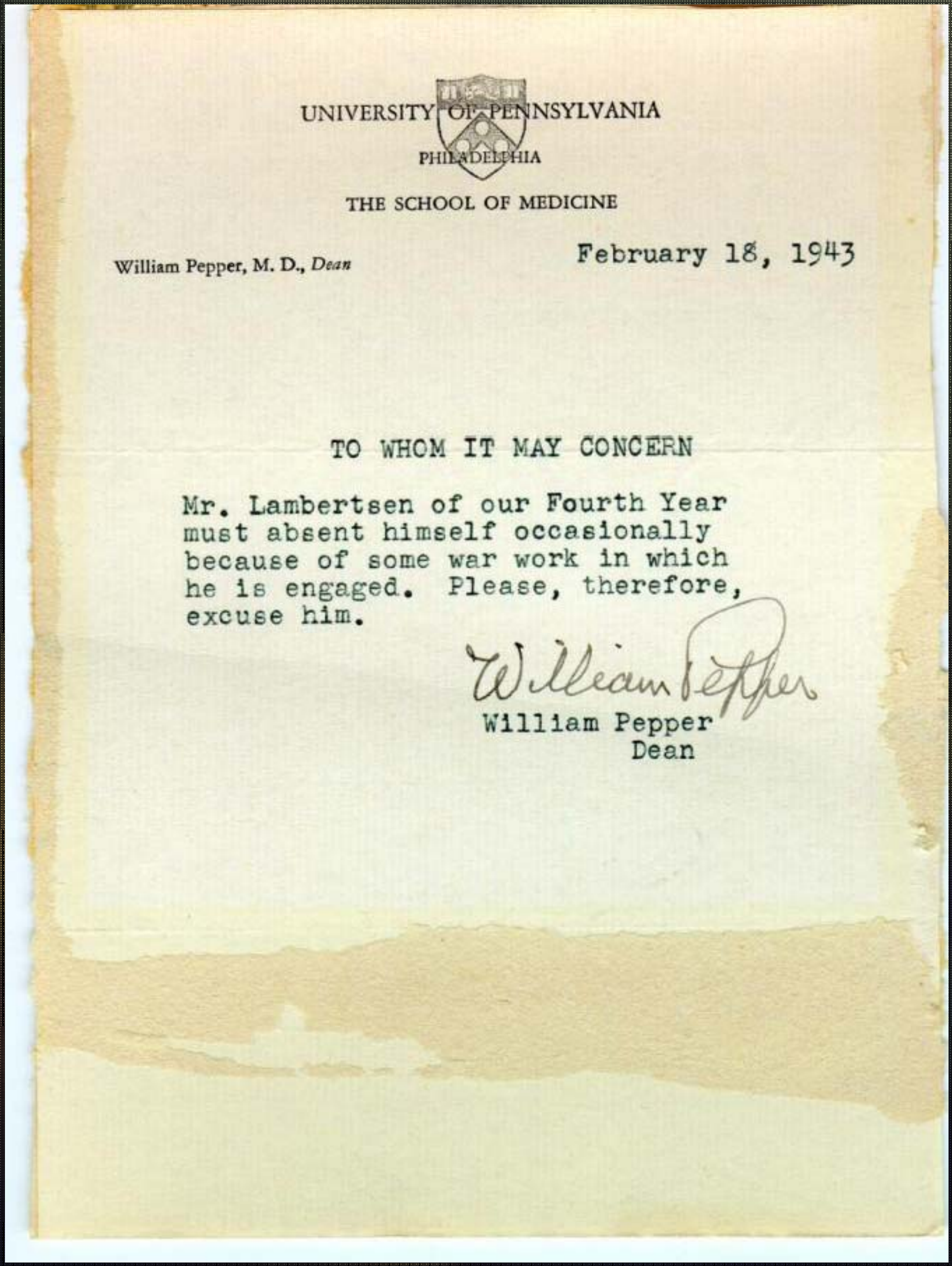

PROCEEDINGS OF THE THIRD SYMPOSIUM ON
Underwater Physiology
edited by C. J. LAMBERTSEN


UNDERWATER PHYSIOLOGY V
Edited by C. J. Lambertsen

Doctor, Scientist, Engineer, Operator, Mentor, Friend

- Invented the Lambertsen Amphibious Respiratory Unit, (LARU) and implemented with the Office of Strategic Services during WWII
- Considered the Father of U.S. Combat Swimming & SCUBA

Military Service


UNIVERSITY OF PENNSYLVANIA
PHILADELPHIA
THE SCHOOL OF MEDICINE

William Pepper, M. D., *Dean*

February 18, 1943

TO WHOM IT MAY CONCERN

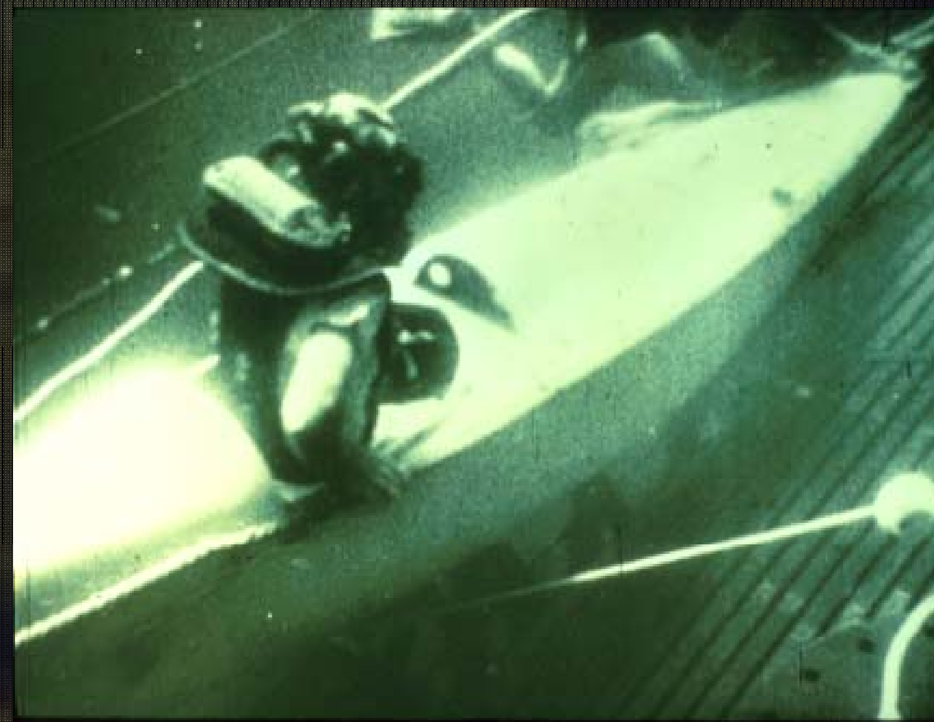
Mr. Lambertsen of our Fourth Year must absent himself occasionally because of some war work in which he is engaged. Please, therefore, excuse him.

William Pepper

William Pepper
Dean

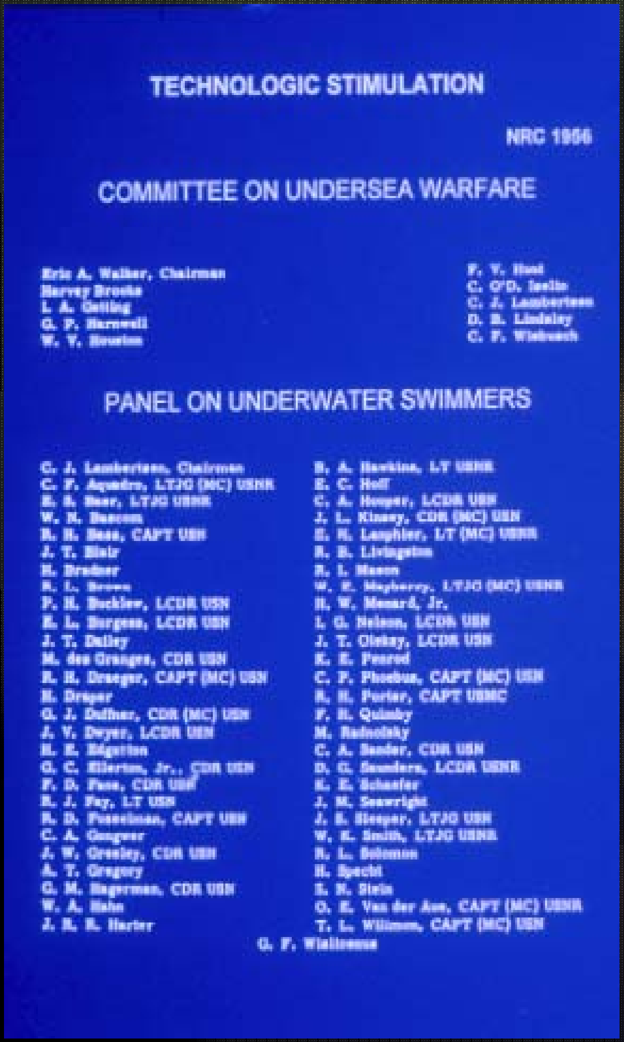
Military Physiology, Engineering, Operations and Training

- Designed and implemented the first submarine lockout dives, and the first mini-sub excursions
- Developed many of the strategic and tactical methods for underwater warfare



Support of National Interests

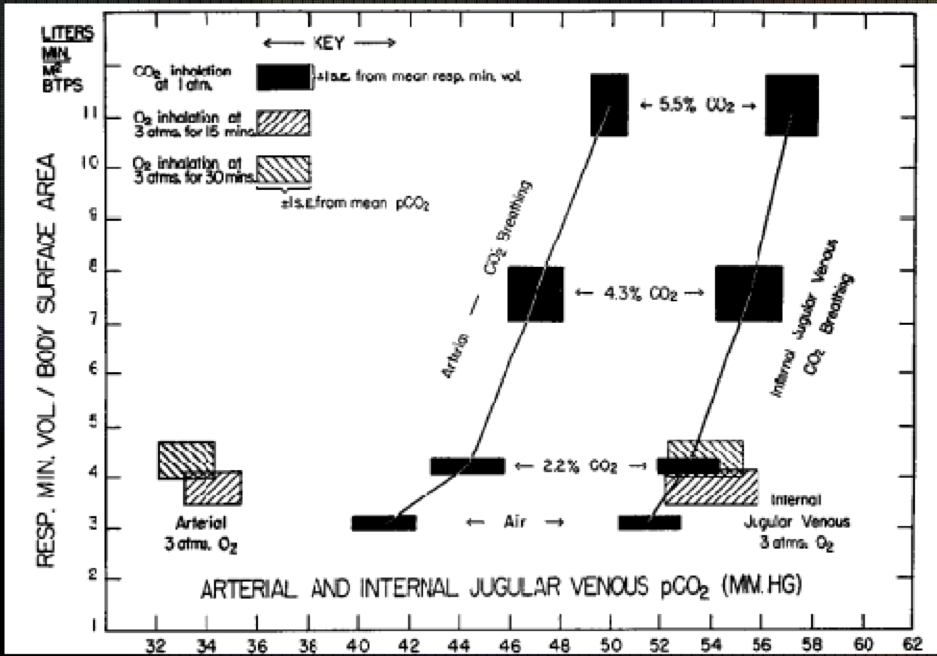
- Served as Chairman and member of countless national military, research and scientific councils and advisory boards over almost 5 decades

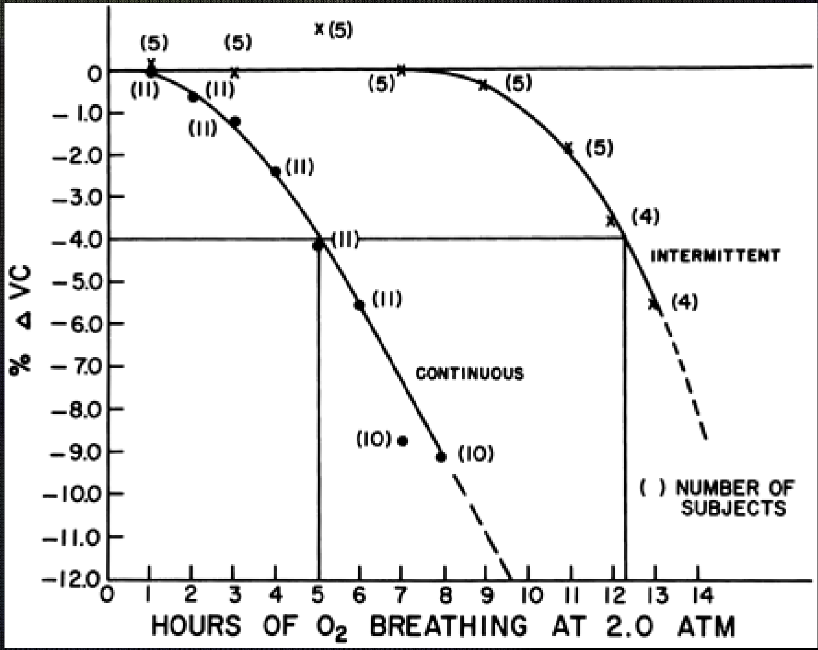


- 1953–1960, 1962–1971 Committee on Naval Medical Research, National Research Council
- 1953–1972 Committee on Undersea Warfare, National Research Council
- 1953–1956 Chairman, Panel on Underwater Swimmers, Committee on Undersea Warfare, National Research Council
- 1954–1960 Chairman, Panel on Shipboard and Submarine Medicine, Committee on Naval Medicine Research, National Research Council
- 1954–1961 Advisory Panel on Medical Sciences, Office of Assistant Secretary of Defense, R and E
- 1955–1959 Consultant, U.S. Army Chemical Corps
- 1959–1961 Consultant, Scientific Advisory Board, U.S. Air Force
- 1960–1962 Chairman, Committee on Man-in-Space, Space Science Board, National Academy of Sciences
- 1960–1962 Member, Space Science Board, National Academy of Sciences
- 1962–1980 Consultant, Space Science Board, National Academy of Sciences
- 1967–1970 Member, President's Space Panel, PSAC
- 1968–1977 Oceanographic Advisory Committee, Office of Secretary of the Navy
- 1972 Consultant to the Diving Physiology and Technology Panel, U.S.-Japan Cooperative Program in Natural Resources, U.S. Department of the Interior
- 1972–1977 Biomedical Sciences Advisor, National Oceanic and Atmospheric Administration, U.S. Dept. of Commerce
- 1973–1977 Member, The Marine Board, National Academy of Engineering
- 1973 Member, Smithsonian Advisory Board
- 1983 Chairman, Environmental Sciences Review Committee, National Aeronautics and Space Administration (NASA)
- 1983–1986 National Undersea Research Center Advisory Board, National Oceanic and Atmospheric Administration
- 1983–1985 Space Medicine Advisory Panel, National Aeronautics and Space Administration
- 1984–1986 Lunar Base Planning Group, National Aeronautics and Space Administration
- 1989–1991 NASA Radiation and Environmental Health Working Group
- 1991–1993 NASA Life Sciences Division Environmental Biomedical Sciences Working Group
- 1992 NASA Life Sciences. Science and Technical Requirements Document for Space Station Freedom
- 1993 NASA JSC Medical Advisory Board, Hubble Telescope Repair EVA
- 1995 NASA JSC “In-Suit” Doppler Panel
- 1998 Chairman, NASA Advisory Panel, Committee on ISS Decompression Risk Definition & Contingency Plan
- 1998–1999 Chairman, NASA Life Sciences Decompression Research Peer Reviews

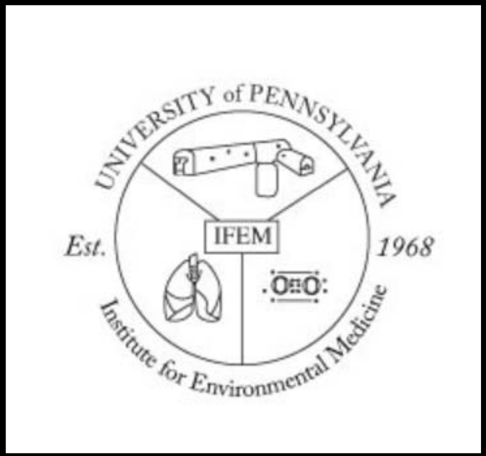
Physiological Studies

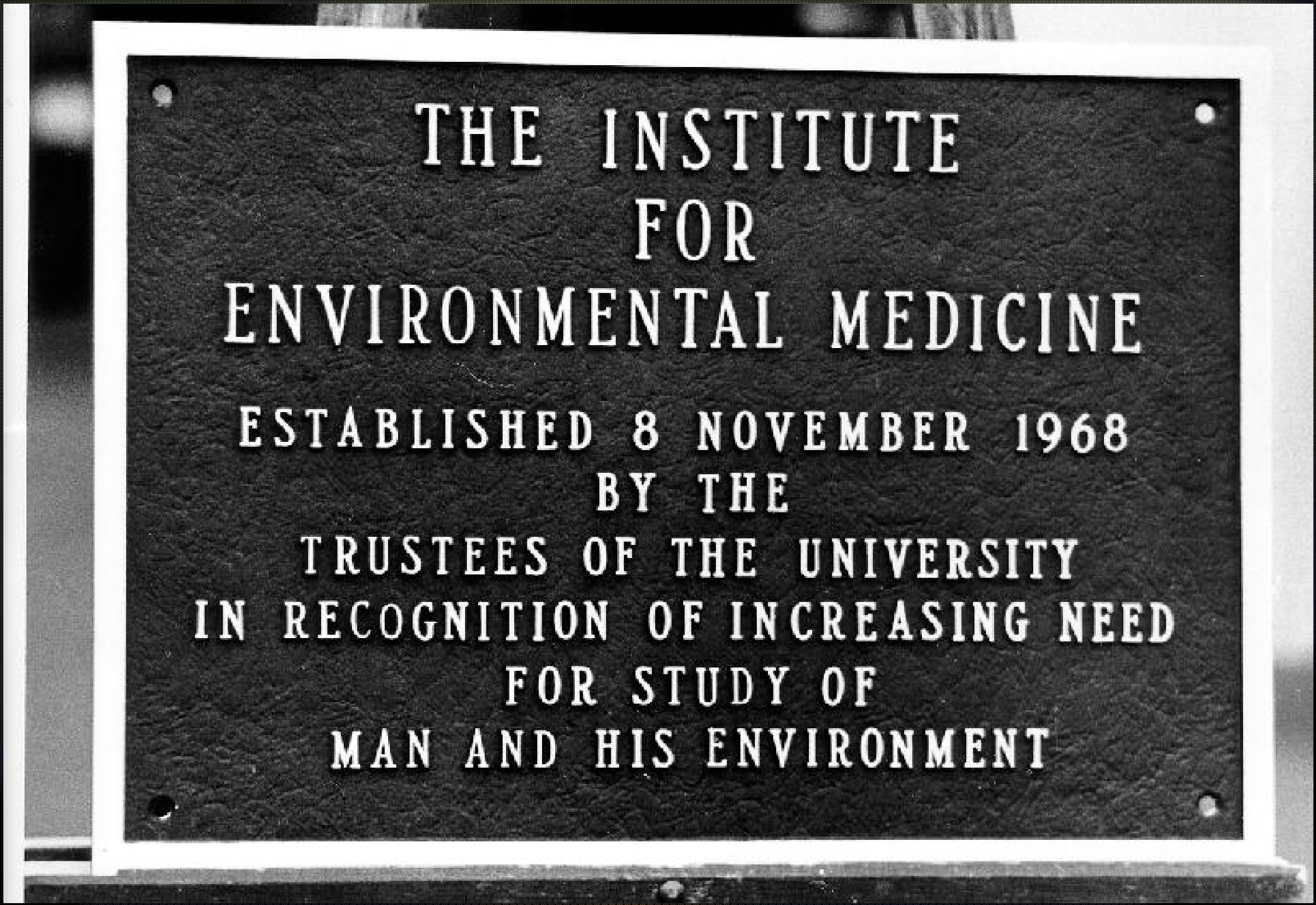
- Worked throughout the 50's and 60's performing physiological studies to understand the mechanisms and control of respiration, oxygen toxicity, C02 and other environmental stress associated with hyperbaric exposures

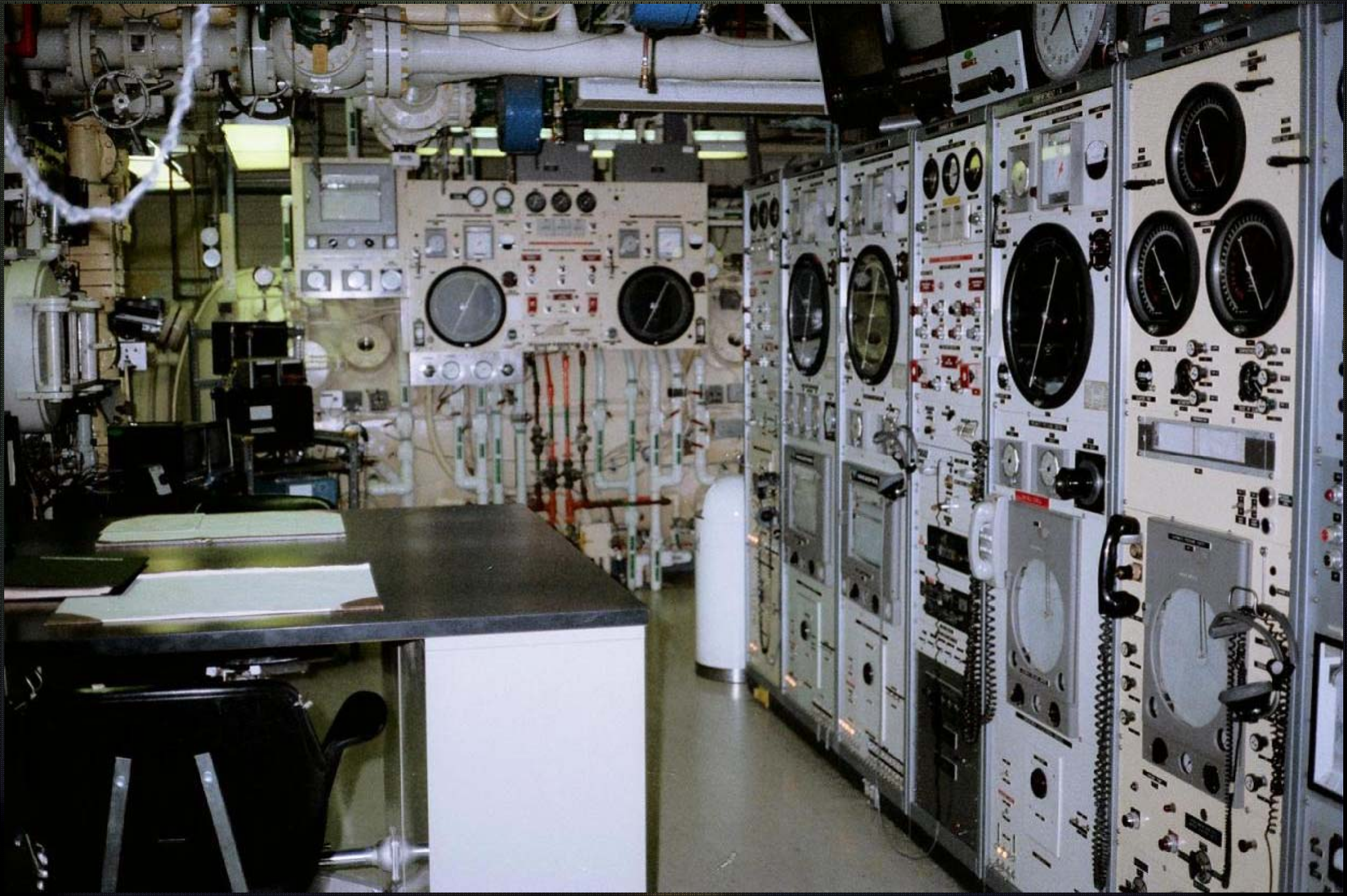




- Chief Life Scientist for the Mercury and Gemini programs
- Founded the Institute of Environmental Medicine at the University of Pennsylvania



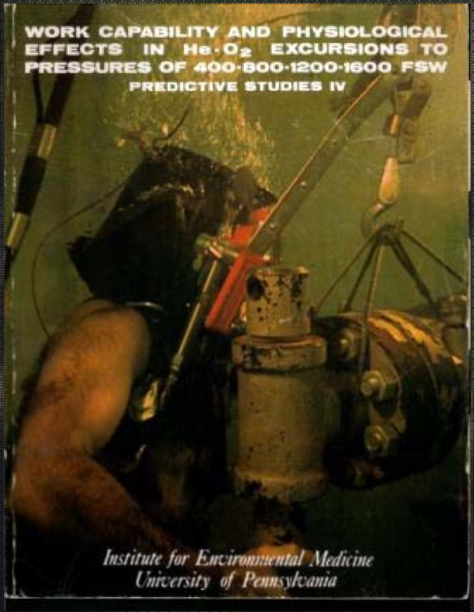

THE INSTITUTE
FOR
ENVIRONMENTAL MEDICINE
ESTABLISHED 8 NOVEMBER 1968
BY THE
TRUSTEES OF THE UNIVERSITY
IN RECOGNITION OF INCREASING NEED
FOR STUDY OF
MAN AND HIS ENVIRONMENT

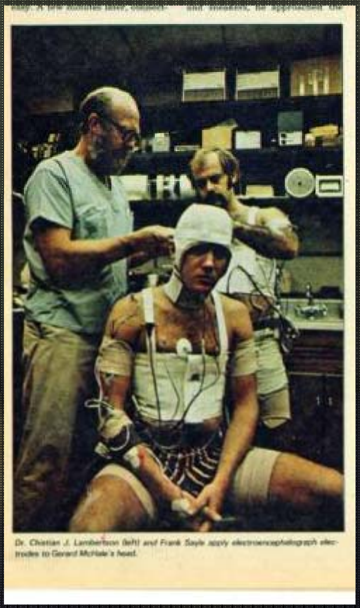


Dr. Lambertsen was at the intersection of Sea and Space, Physiology, Engineering and Operations

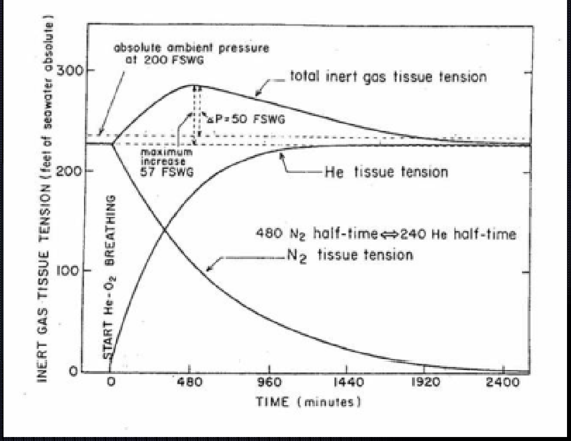
Predictive Studies

- Predictive studies Series beginning with Tektite in 1969 through Predictive Studies 5 in late 90’s

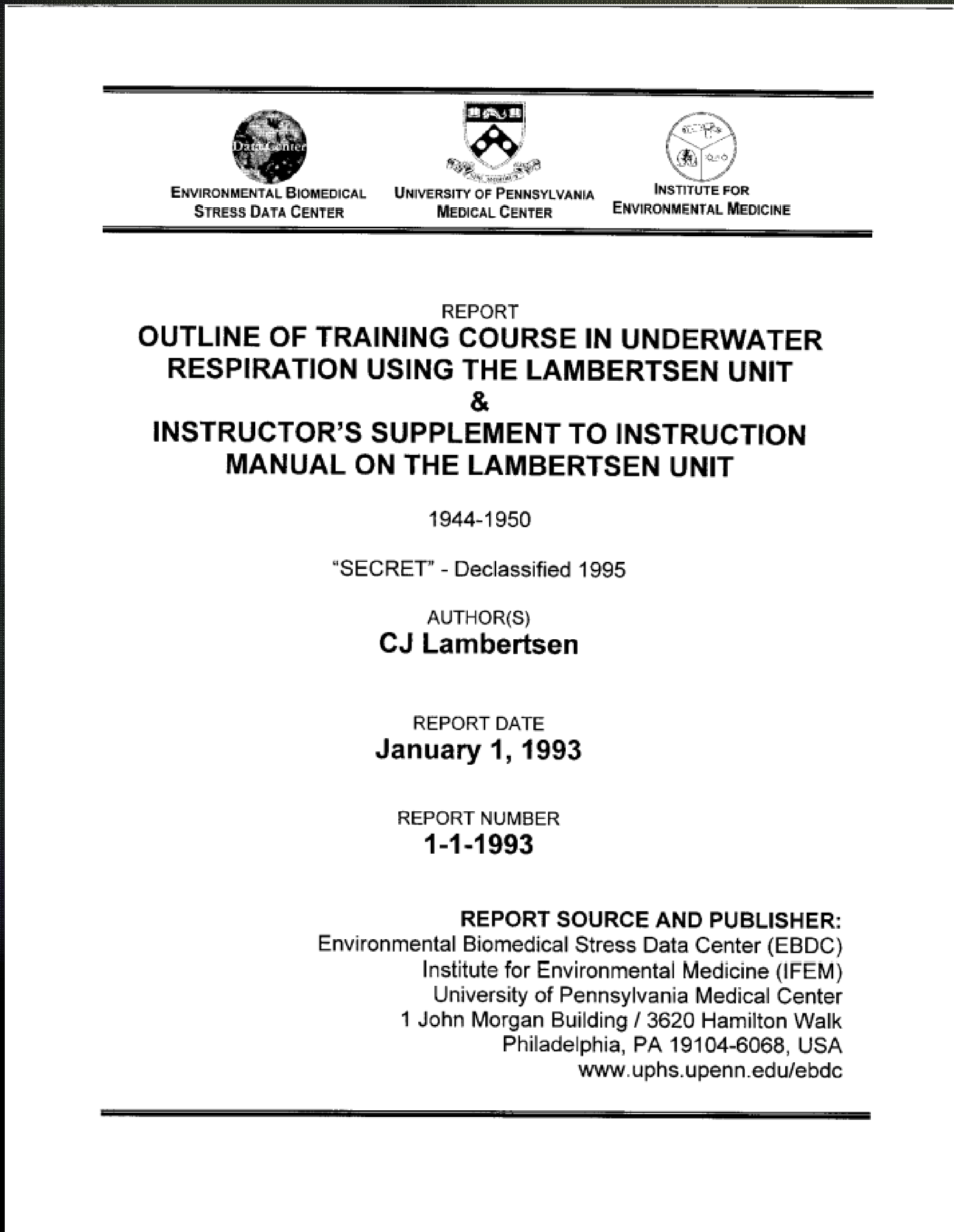




- Discovered Isobaric Counter-Diffusion (Lambertsen’s disease)



Medical Training



ENVIRONMENTAL BIOMEDICAL STRESS DATA CENTER
UNIVERSITY OF PENNSYLVANIA MEDICAL CENTER
INSTITUTE FOR ENVIRONMENTAL MEDICINE

REPORT

OUTLINE OF TRAINING COURSE IN UNDERWATER RESPIRATION USING THE LAMBERTSEN UNIT
&
INSTRUCTOR'S SUPPLEMENT TO INSTRUCTION MANUAL ON THE LAMBERTSEN UNIT

1944-1950

"SECRET" - Declassified 1995

AUTHOR(S)
CJ Lambertsen

REPORT DATE
January 1, 1993

REPORT NUMBER
1-1-1993

REPORT SOURCE AND PUBLISHER:
Environmental Biomedical Stress Data Center (EBDC)
Institute for Environmental Medicine (IFEM)
University of Pennsylvania Medical Center
1 John Morgan Building / 3620 Hamilton Walk
Philadelphia, PA 19104-6068, USA
www.uphs.upenn.edu/ebdc

- Training of Diving Doctors for over 5 decades - from George Bond to Les Fenton

Founder of the UHMS

UNDERSEA & HYPERBARIC MEDICAL SOCIETY

Appointed Al Benke as the Societies first President

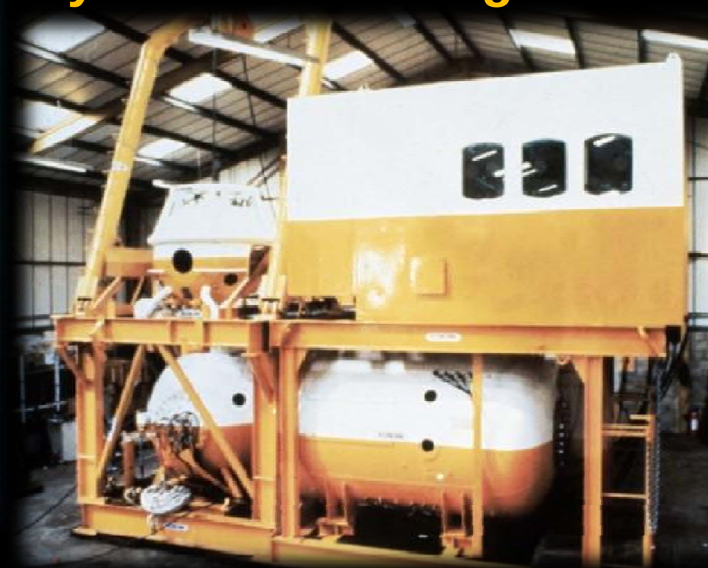
“ What do you need to do, and then how do you do it safely?”

“ Do it sensibly”

“Measure Big things so you can see a difference and learn something”

“Models are tools to help you to think, not to stop you from thinking”

His hand touched nearly every aspect of diving and space operations



“ just remember these are paper bubbles”

“Don’t let the bastards get you down”

University and National Civilian Awards and Honors

- 1948–1953 John and Mary R. Markle Scholar in Medical Science
- 1965 University of Pennsylvania Alumni Award of Merit
- 1967 Lindback Award for Distinguished Teaching
- 1969 NASA Commendation
- 1970 Aerospace Medical Association Award
- 1970 Undersea Medical Society Award
- 1972 Marine Technology Society Award for Ocean Science and Engineering
- 1973 Underwater Society of America Award for Science
- 1974 New York Academy of Sciences Award for Research in Environmental Science
- 1977 Member, National Academy of Engineering
- 1977 Doctor of Science Honorary Degree, Northwestern University
- 1977 Fellow, College of Physicians of Philadelphia
- 1978 Distinguished Award for Individuals, Offshore Technology Conference
- 1979 Award in Environmental Science, Aerospace Medical Association
- 1979 Award for Naval Undersea Research Training, Undersea Medical Society
- 1980 Association of Diving Contractors Award
- 1984 Endowed Visiting Lectureship, Sterling Pharmaceutical Corporation
- 1989 Distinguished Medical Graduate Award, University of Pennsylvania
- 1992 Boerema Award, Hyperbaric Oxygen Research, Undersea and Hyperbaric Medical Society
- 1995 UDT-SEAL Association Lifetime Achievement Award
- 1995 Department of Defense Citation
- 1997 UDT-SEAL Association: Honorary Lifetime Membership
- 1999 Beneath the Sea: Lifetime Achievement Award
- 2001 Pioneer Award – Navy Historical Society
- 2001 CJL Oxygen Symposium X, Undersea and Hyperbaric Medical Society
- 2007 American College of Physicians Fellowship Award 2007

Military Service and Related Awards

- 1945 Legion of Merit, U.S. Army
- 1945 Major General William J. Donovan, U.S.A., Director, Office of Strategic Services
- 1945 Lt. Colonel H. Q. A. Reeves, British Army
- 1945 Lt. Commander Derek A. Lee, R.N.V.R., Burma
- 1945 Colonel Sylvester C. Missal, M.C., U.S.A., Chief Surgeon, Office of Strategic Services
- 1945 Commander H. G. A. Wooley, D.S.C., R.N., Director, Maritime Unit, Office of Strategic Services
- 1946 Presidential Unit Citation, O.S.S. Unit 101, Burma, Dwight D. Eisenhower
- 1946 U.S. Army Commendation Ribbon, Citation from Major General Norman Kirk, M.C., Surgeon General, U.S. Army
- 1946 Admiral J. F. Farley, Commandant, U.S. Coast Guard
- 1946 Colonel H. W. Doan, M.C., Executive Officer, Surgeon General's Office, U.S. Army
- 1947 Colonel George W. Read, Jr., President, U.S. Army Ground Forces, Board No. 2
- 1948 General Jacob L. Devers, U.S.A. Commanding General, U.S. Army Ground Forces
- 1969 Meritorious Civilian Service Award, Secretary of the Navy
- 1969 Military Oceanography Award, Secretary of the Navy
- 1972 Department of Defense Distinguished Public Service Award
- 1972 Secretary of the Navy Certificate of Commendation for Advisory Service, Committee on Undersea Warfare, National Academy of Sciences
- 1976 Distinguished Public Service Award, United States Coast Guard
- 1978 Certificate of Commendation for Outstanding Service on Secretary of the Navy Oceanographic Advisory Committee
- 1995 British Embassy Citation
- 1995 U.S. Army Special Forces Underwater Operations School Award: Lifetime Achievement
- 1996 U.S. Special Forces Green Beret Award
- 2001 U.S. Special Operations Command Medal
- 2005 US Chief of Naval Operations Citation

National Service Activities

- 1953–1960, 1962–1971 Committee on Naval Medical Research, National Research Council
- 1953–1972 Committee on Undersea Warfare, National Research Council
- 1953–1956 Chairman, Panel on Underwater Swimmers, Committee on Undersea Warfare, National Research Council
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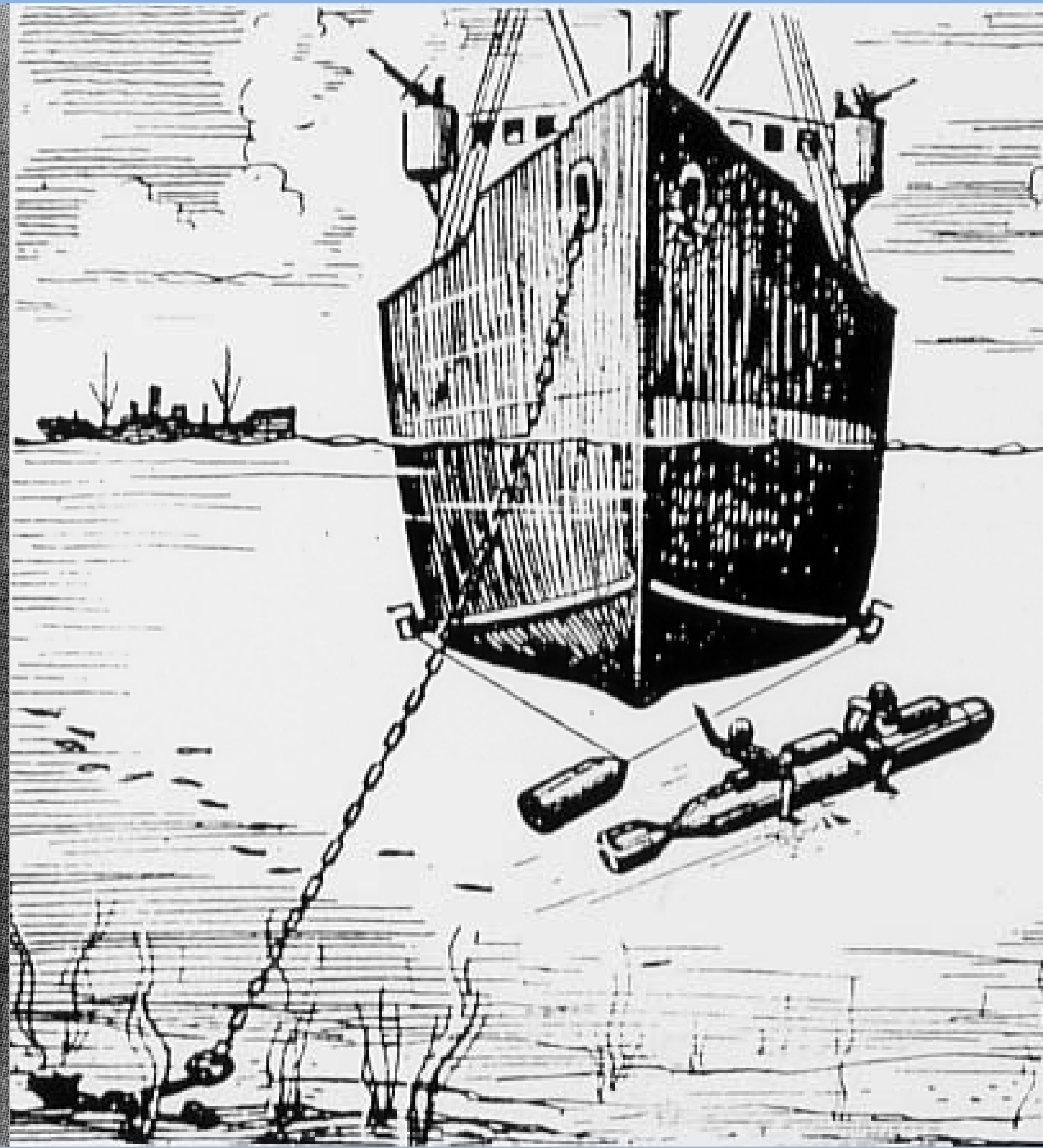
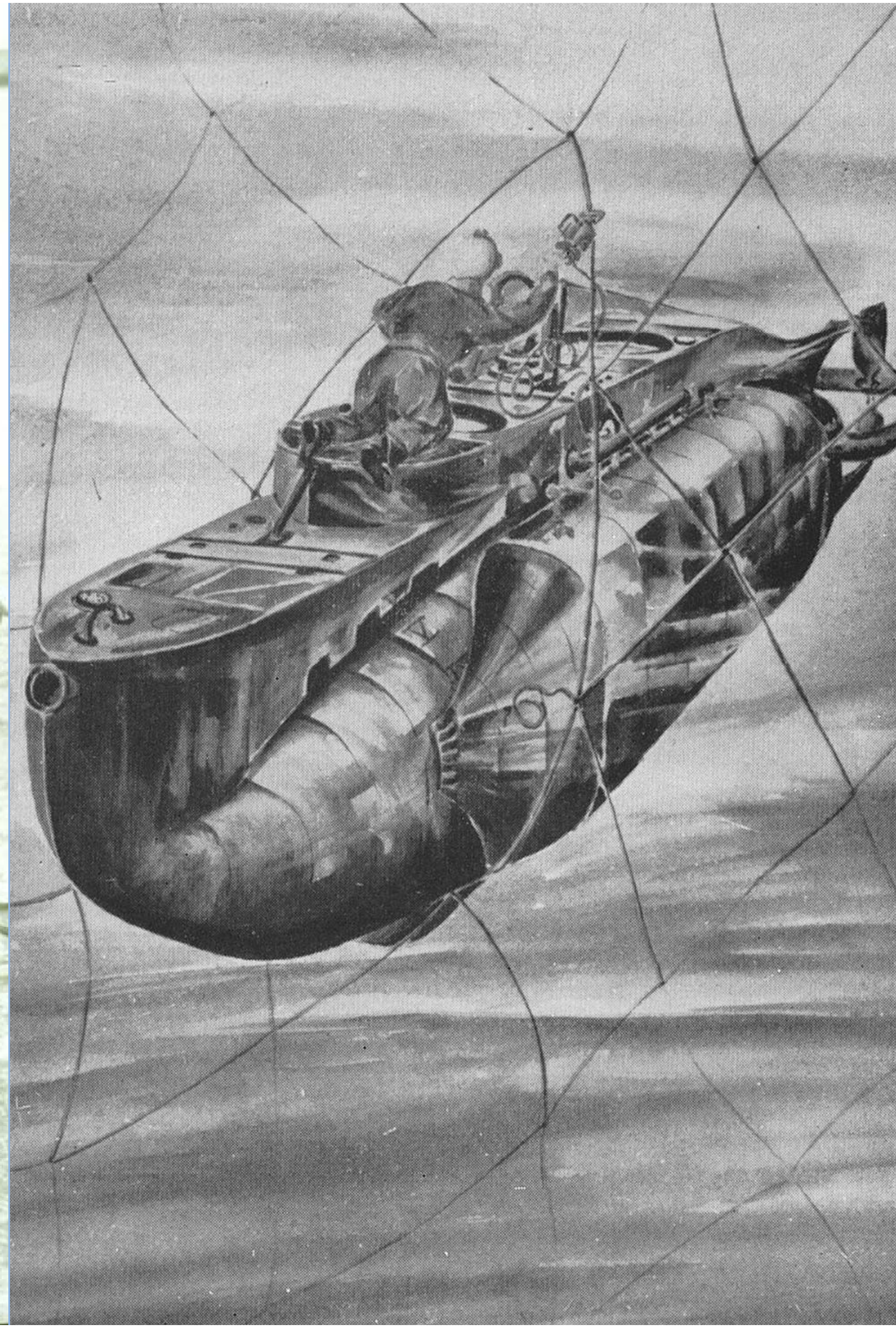
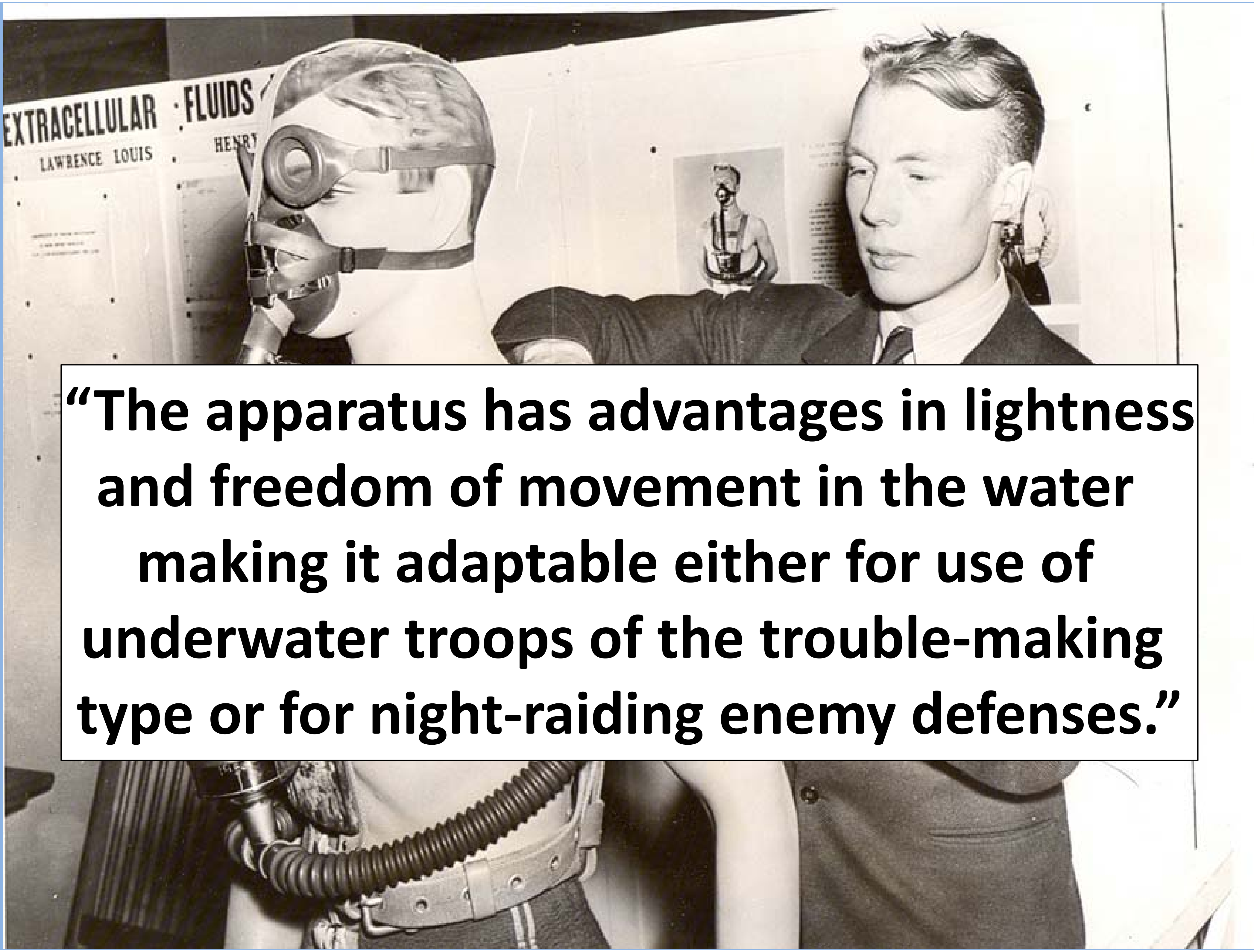
Tribute to the Extraordinary Life's Work of Dr. Christian .J. Lambertsen

Military Contributions

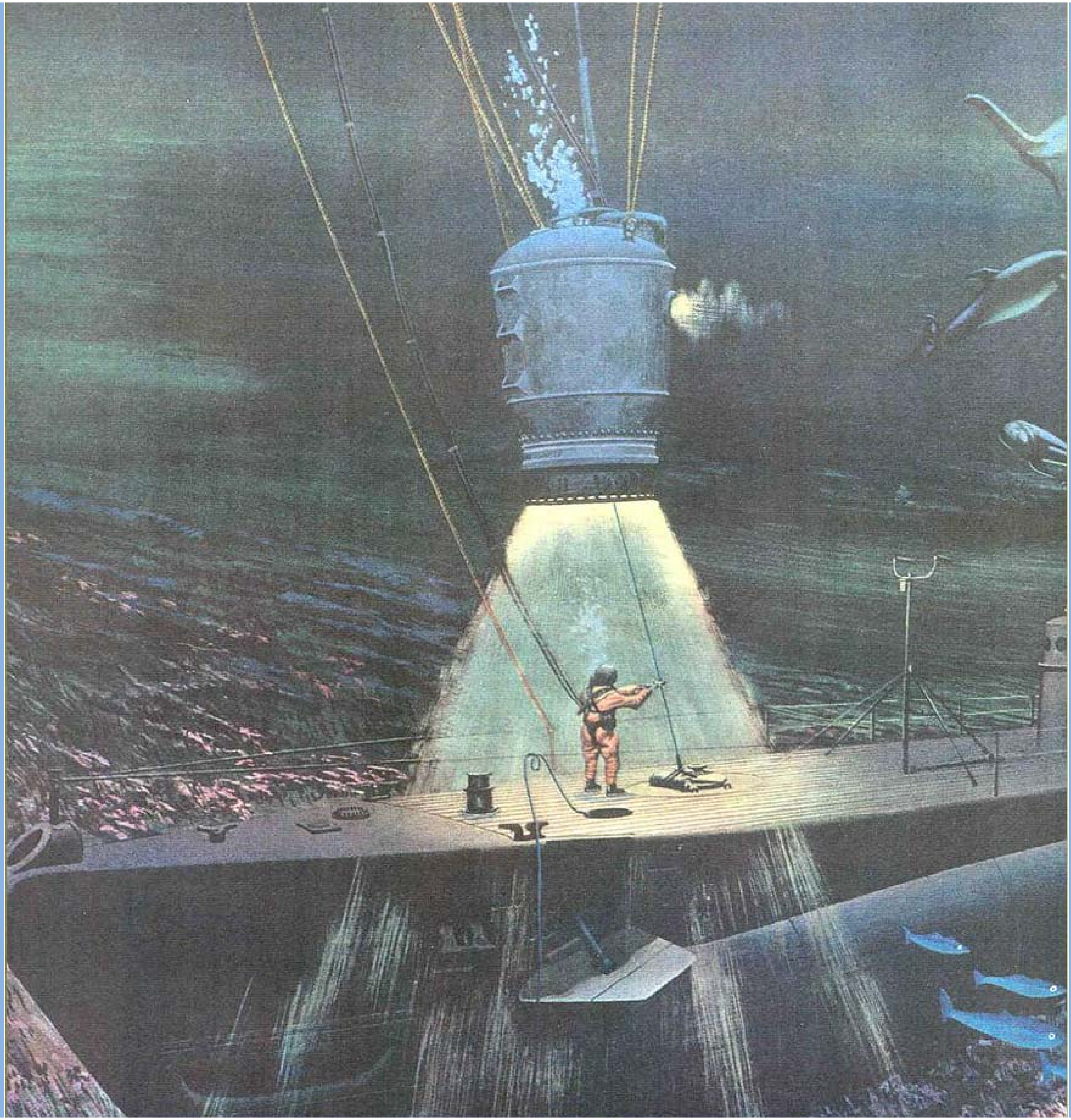
Dr. Richard Vann





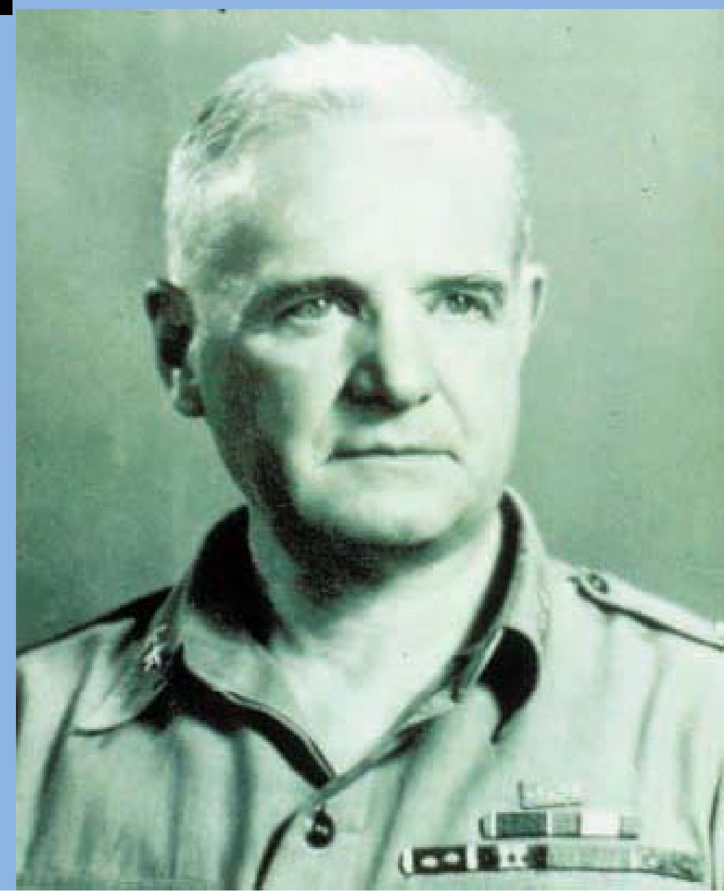
“The apparatus has advantages in lightness and freedom of movement in the water making it adaptable either for use of underwater troops of the trouble-making type or for night-raiding enemy defenses.”

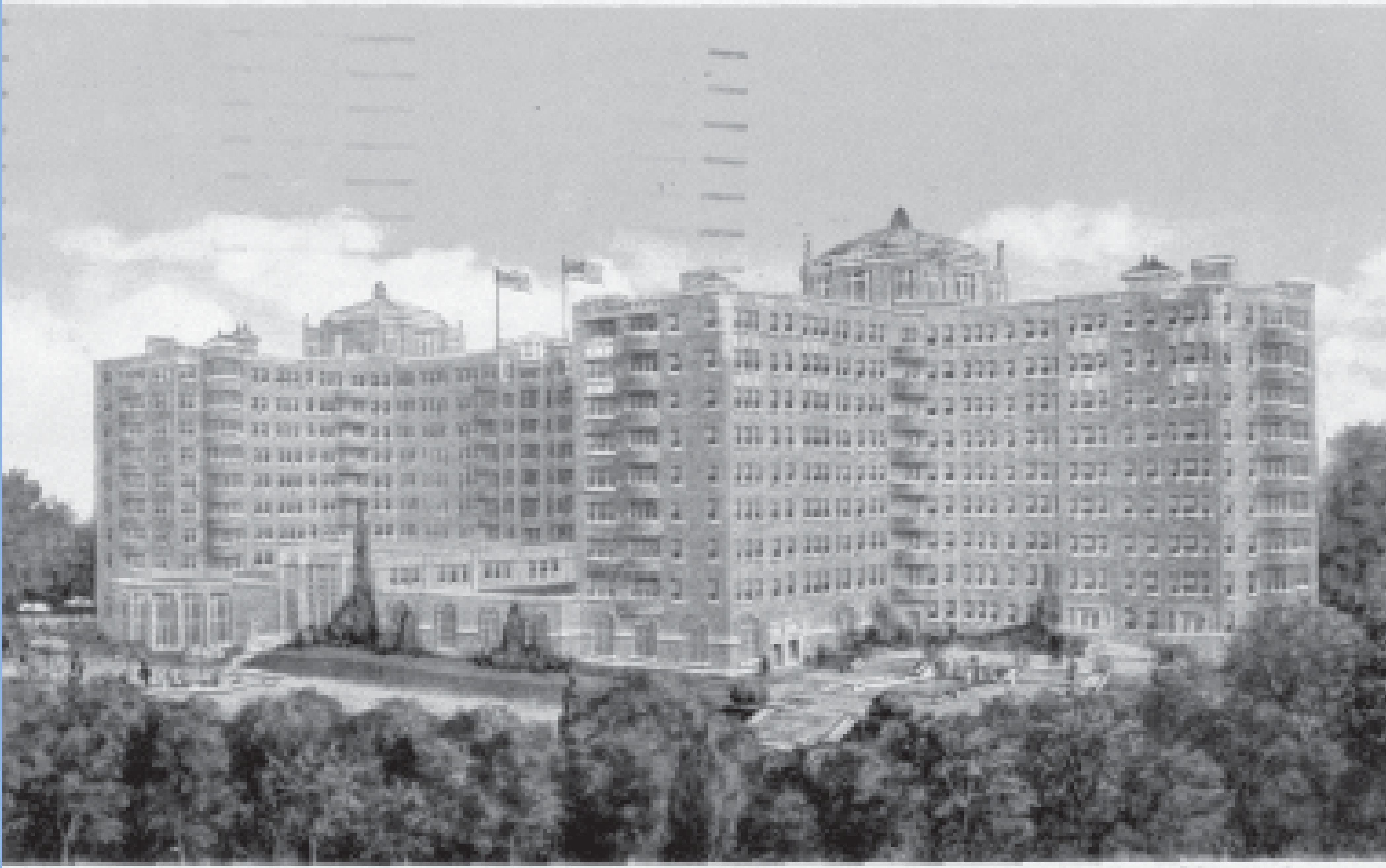


OFFICE OF STRATEGIC SERVICES

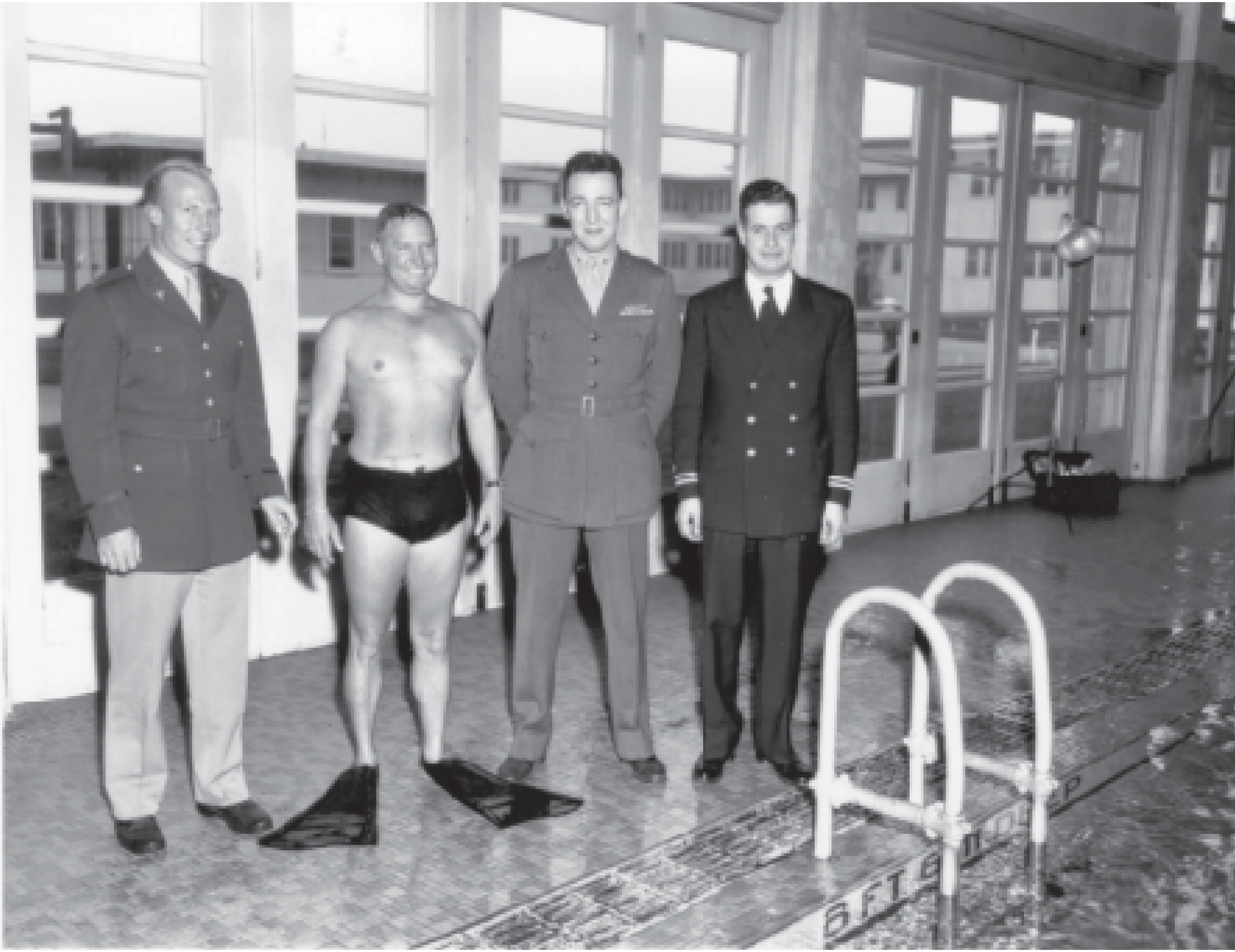
COL Donovan WWI

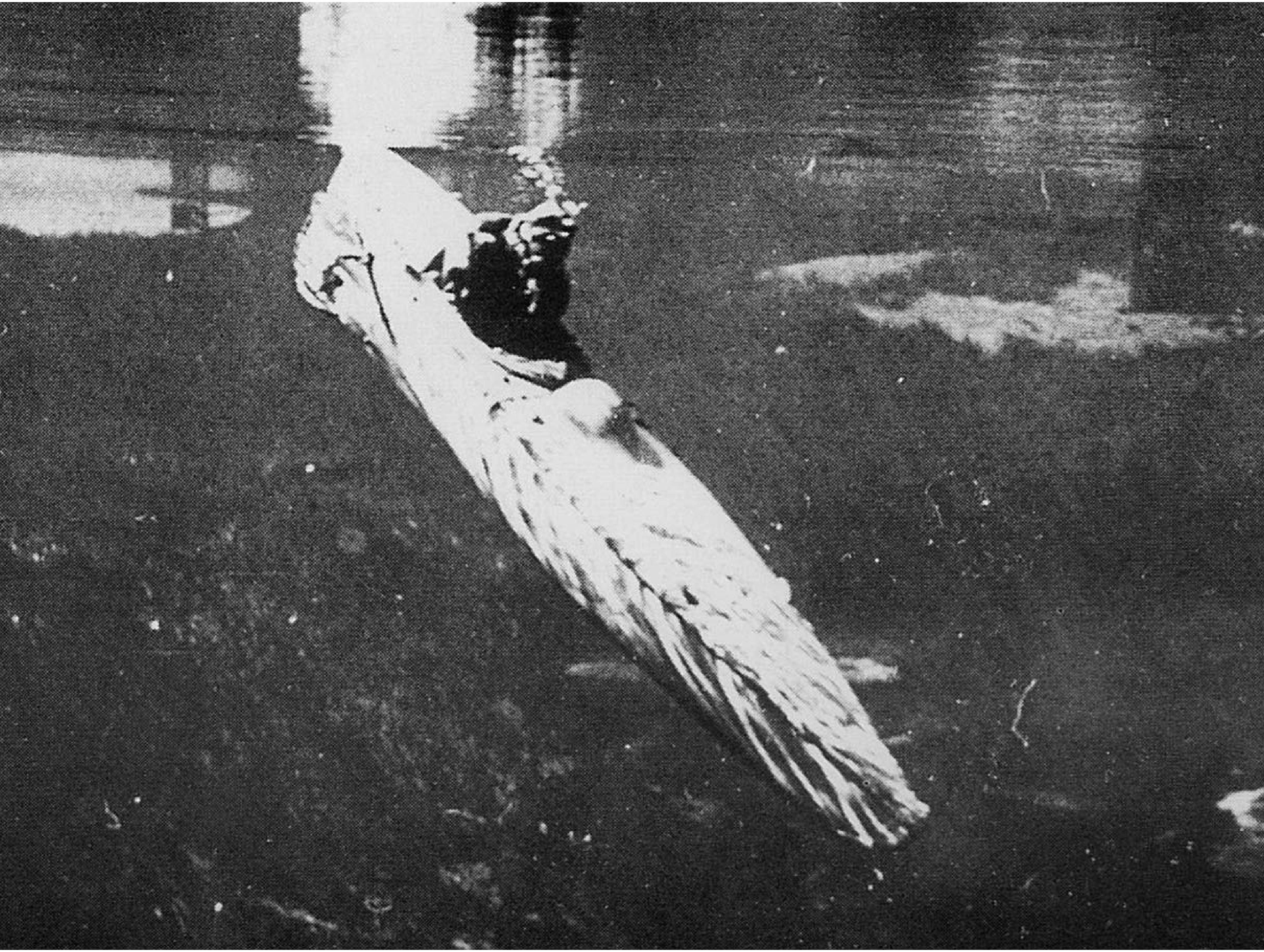
GEN Donovan WWII

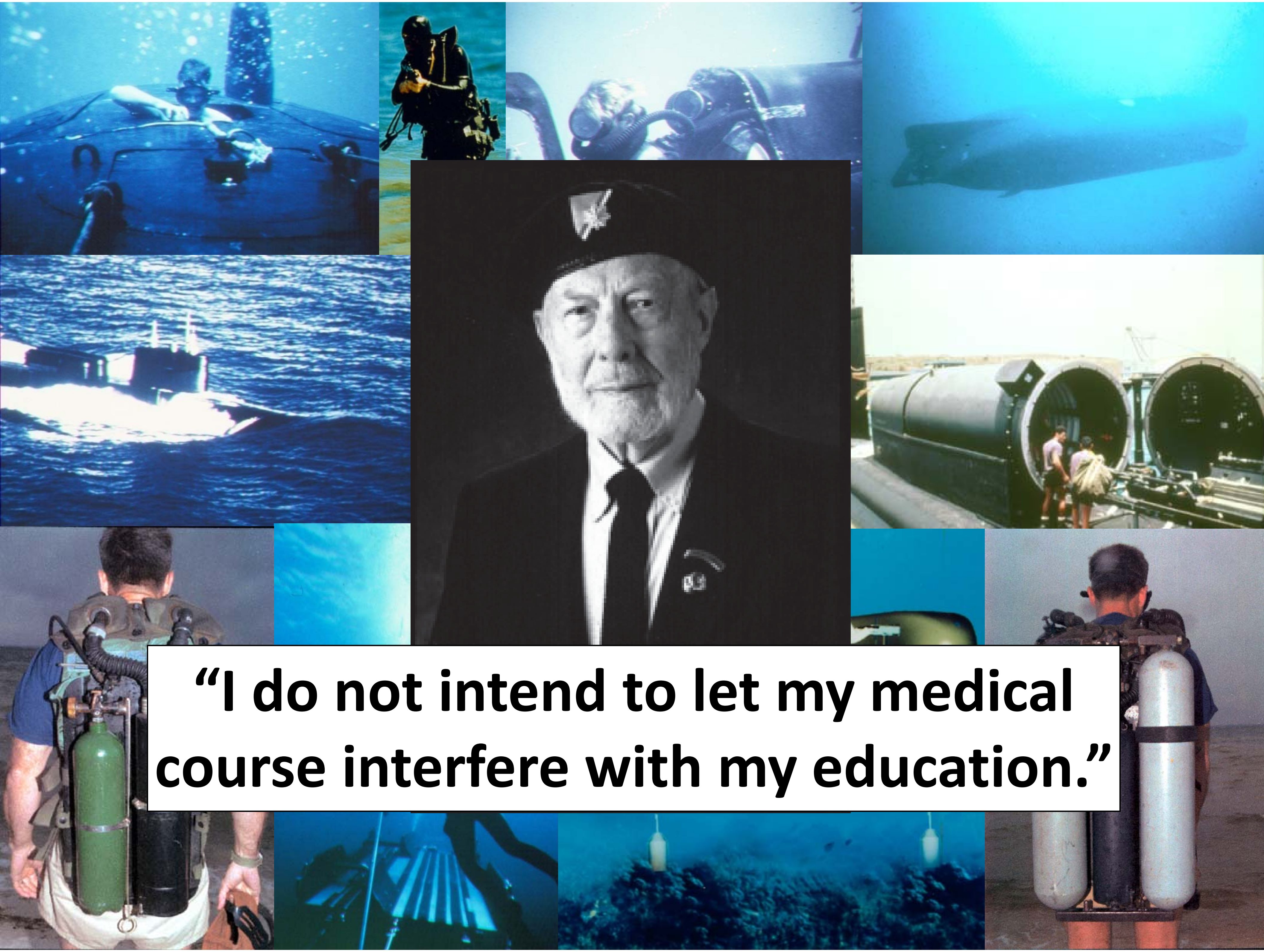


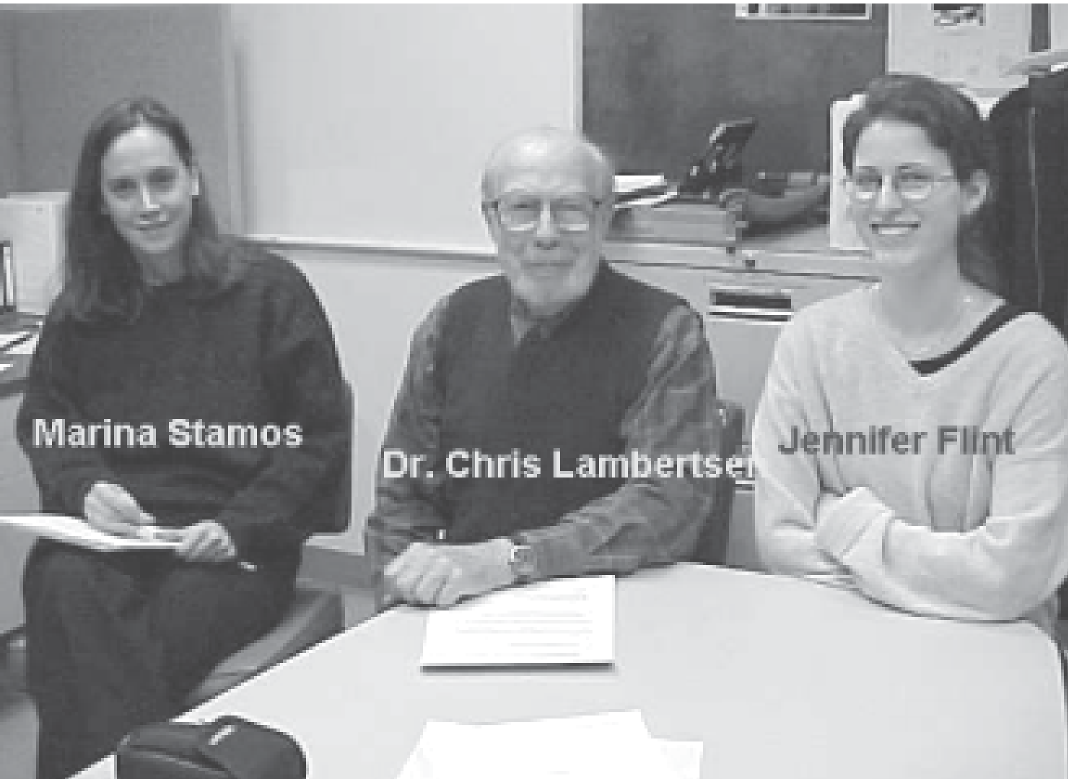


THE SHOREHAM HOTEL • Connecticut Ave. at Calvert St. • WASHINGTON, D. C.






"I do not intend to let my medical course interfere with my education."


Marina Stamos
Dr. Chris Lambertsen
Jennifer Flint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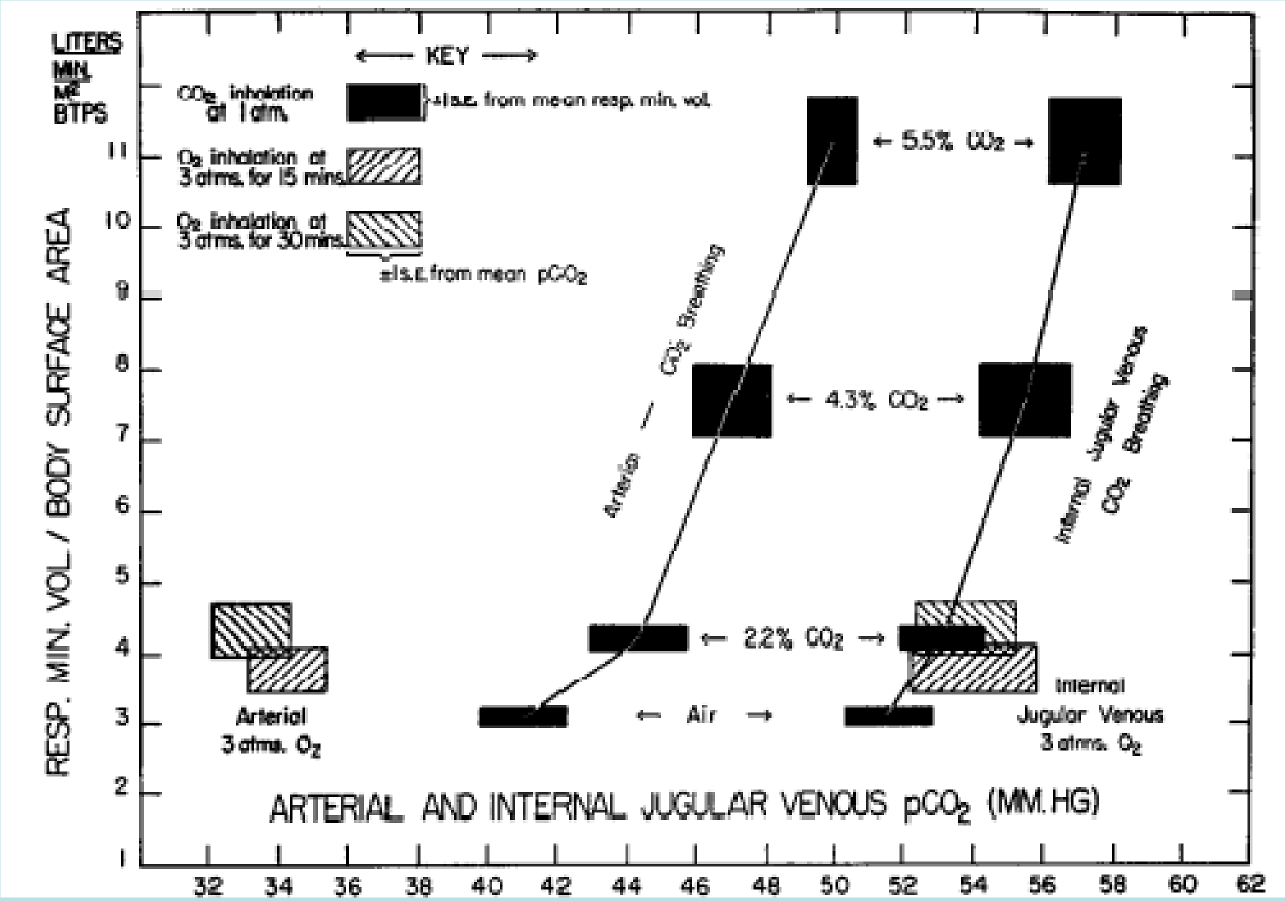
Tribute to the Extraordinary Life's Work of Dr. Christian .J. Lambertsen

Contributions to Oxygen and Respiratory Physiology

Dr. Jim Clark

Respiratory Stimulation by O_2 and CO_2 at 3.0 ATA

J Appl Physiol 5:803-813, 1953

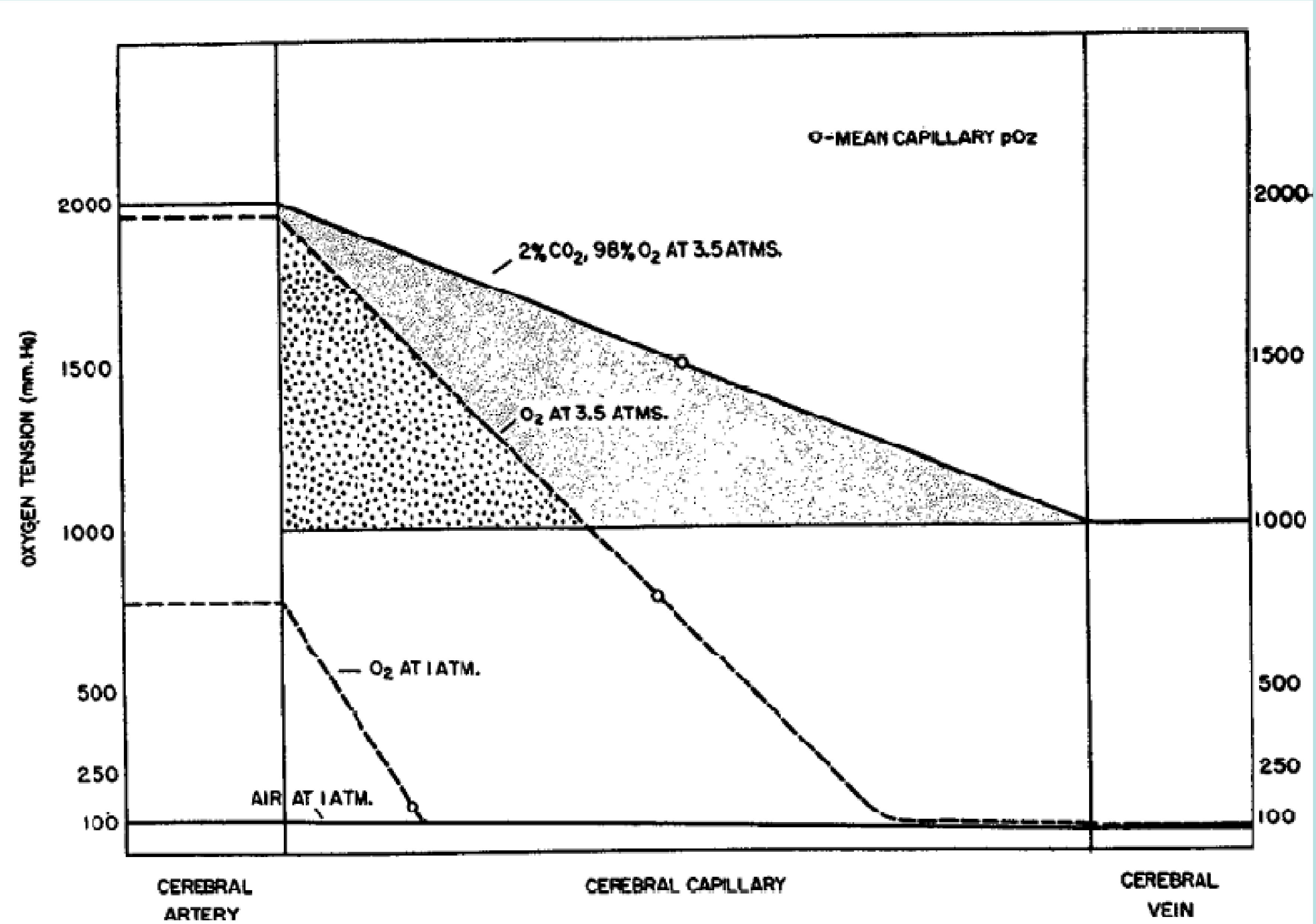


Oxygen Toxicity. Arterial and Internal Jugular Blood Gas Composition in Man During Inhalation of Air, 100% O_2 and 2% CO_2 in O_2 at 3.5 Atmospheres Ambient Pressure[1]

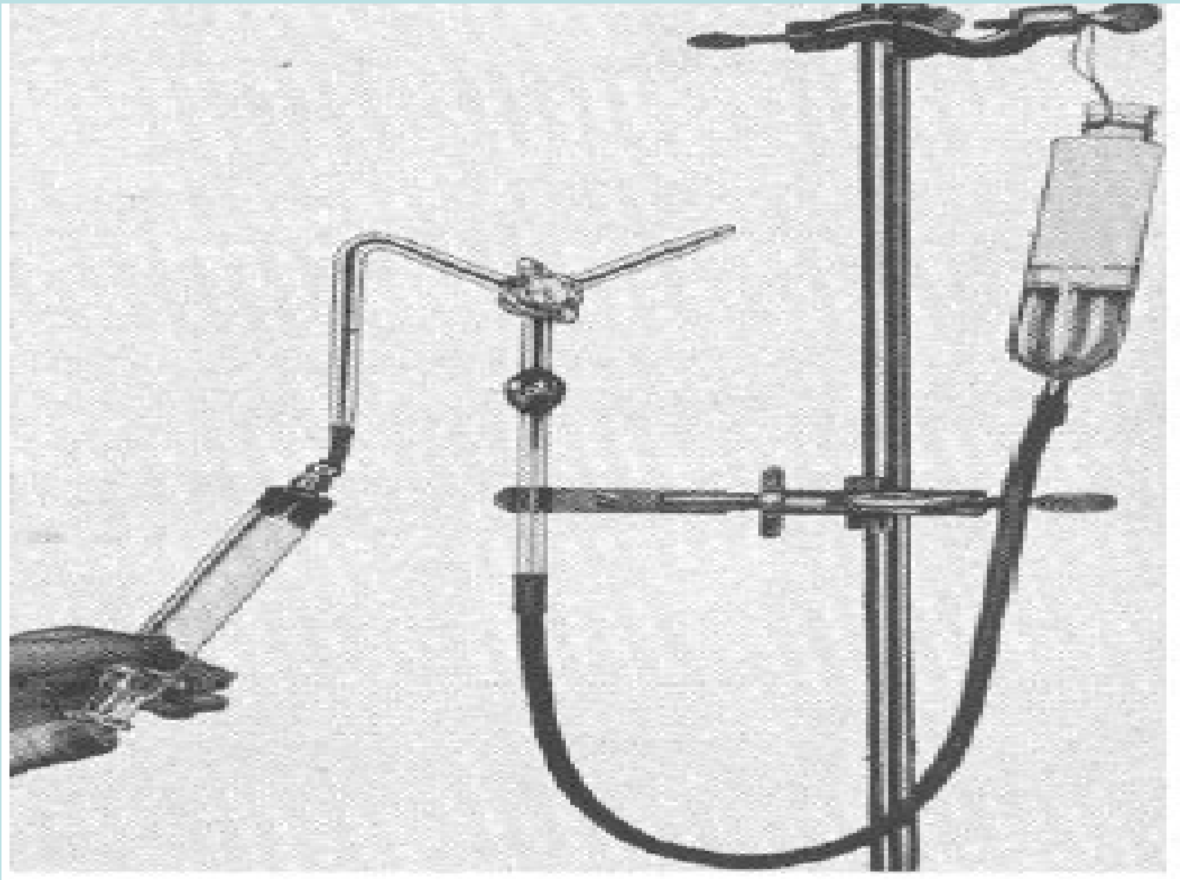
C. J. LAMBERTSEN[2], J. H. EWING, R. H. KOUGH, R. GOULD AND M. W. STROUD 3RD. *From the Laboratory of Pharmacology, University of Pennsylvania School of Medicine, Philadelphia, Pennsylvania*

Effects of O_2 and CO_2 on Brain Oxygenation at 3.5 ATA

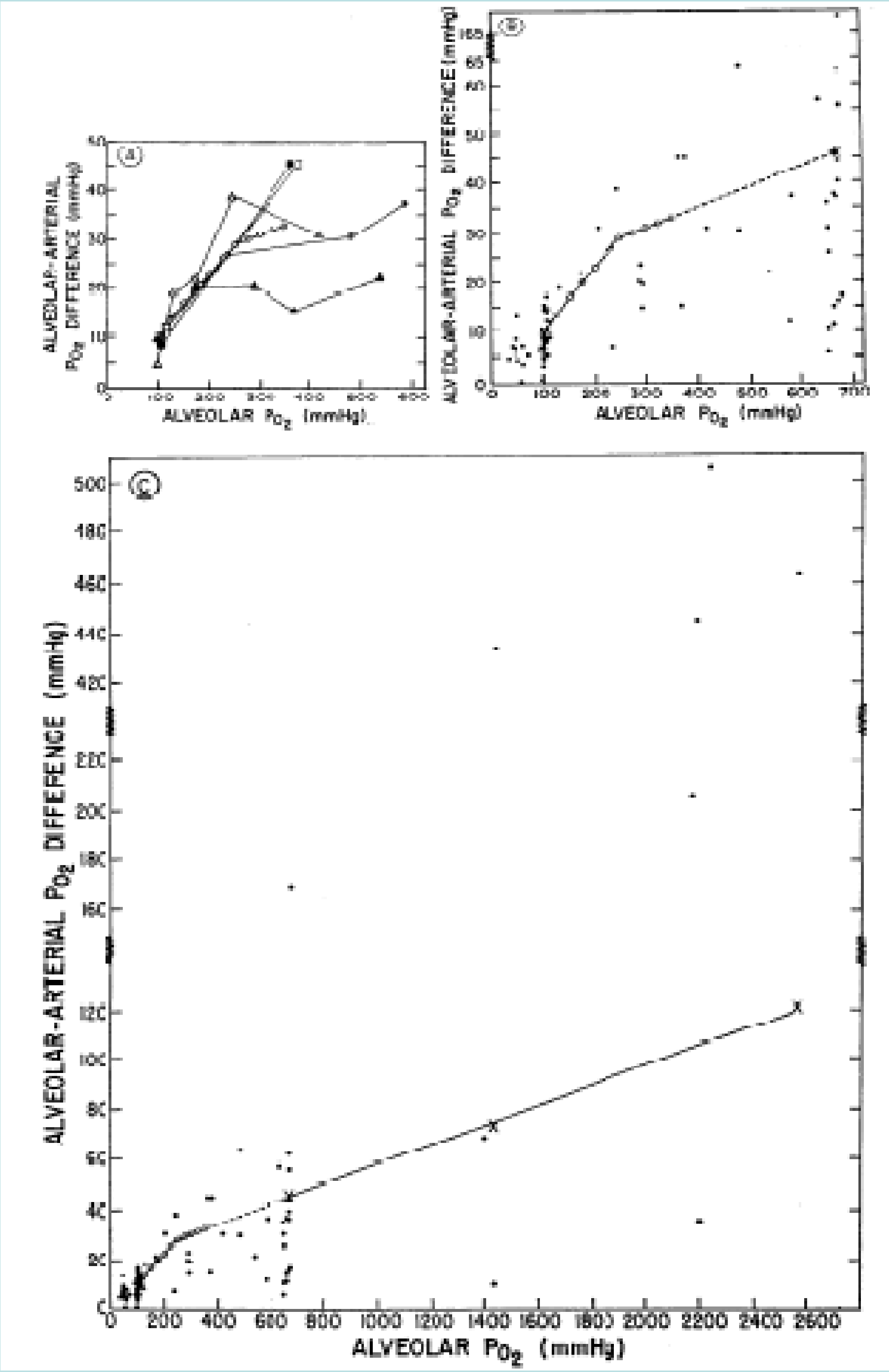
J Appl Physiol 8:255-263, 1955



Anaerobic Pipette



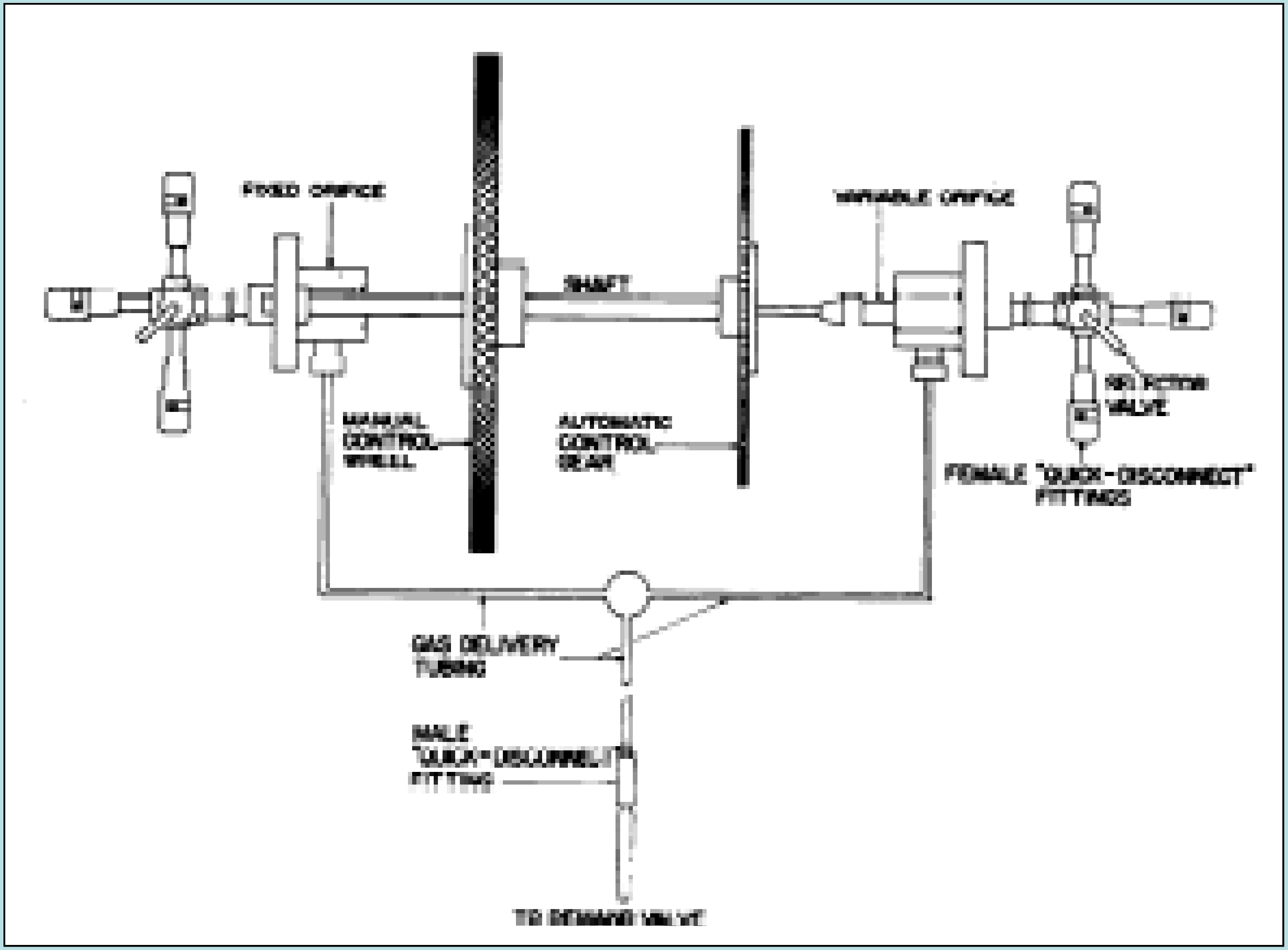
J Appl Physiol 5: 471- 486, 1953



Alveolar-arterial oxygen differences in man at 0.2, 1.0, 2.0, and 3.5 Ata inspired PO_2

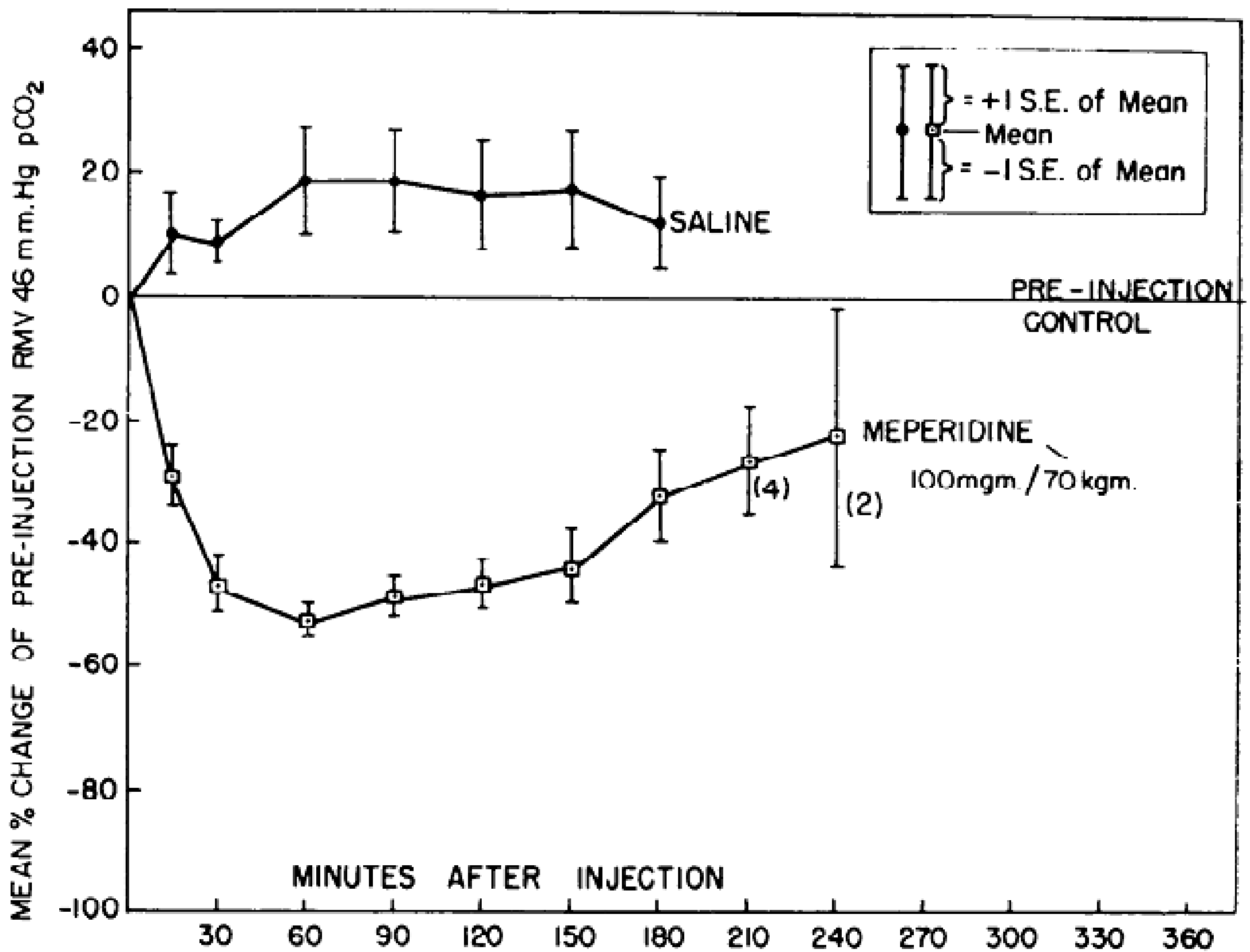
J Appl Physiol 30:753-763, 1971

Gas Ratiometer



Narcotic Depression of Ventilation

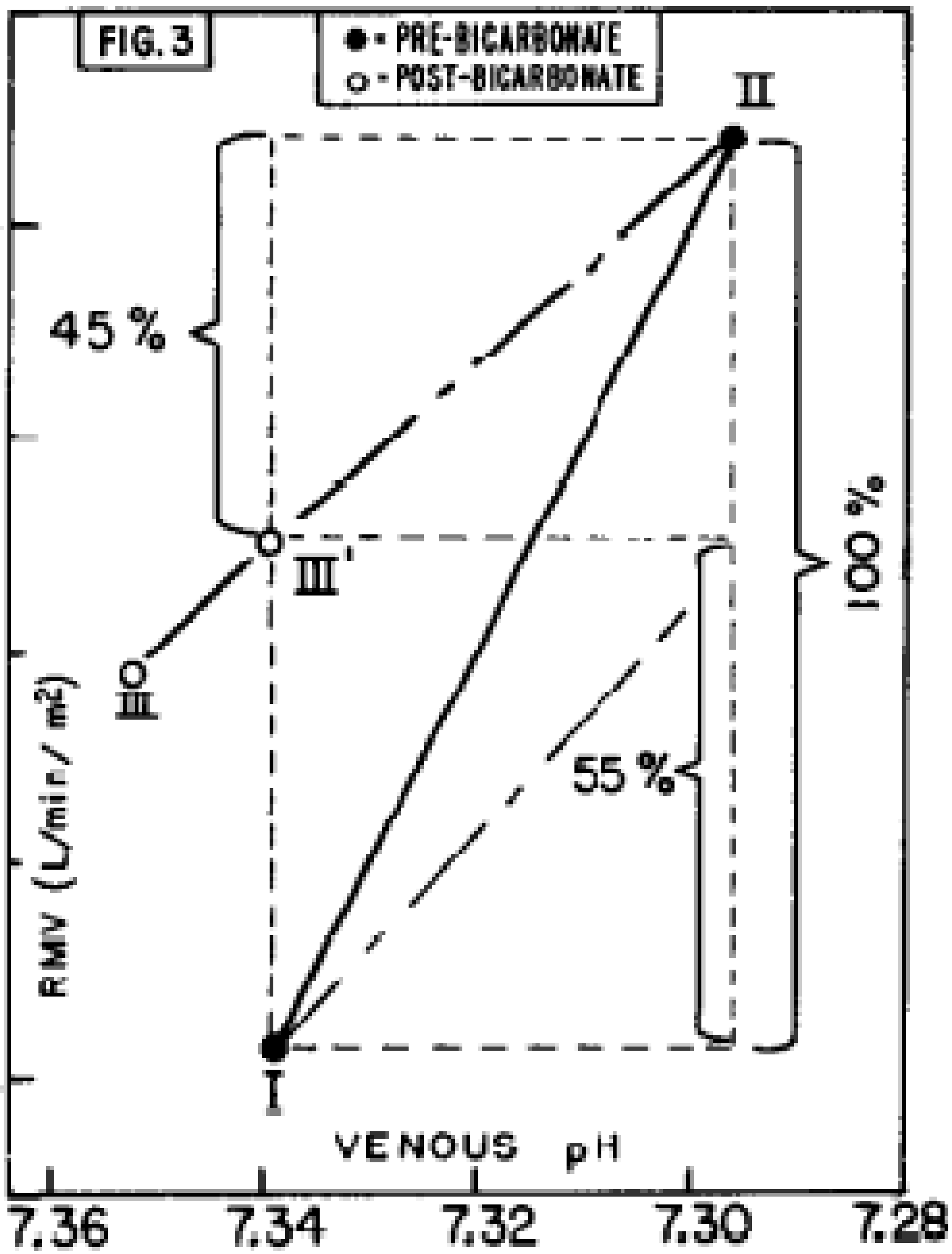
J Appl Physiol 15:43-48, 1960



Respiratory responses to changes in blood pH

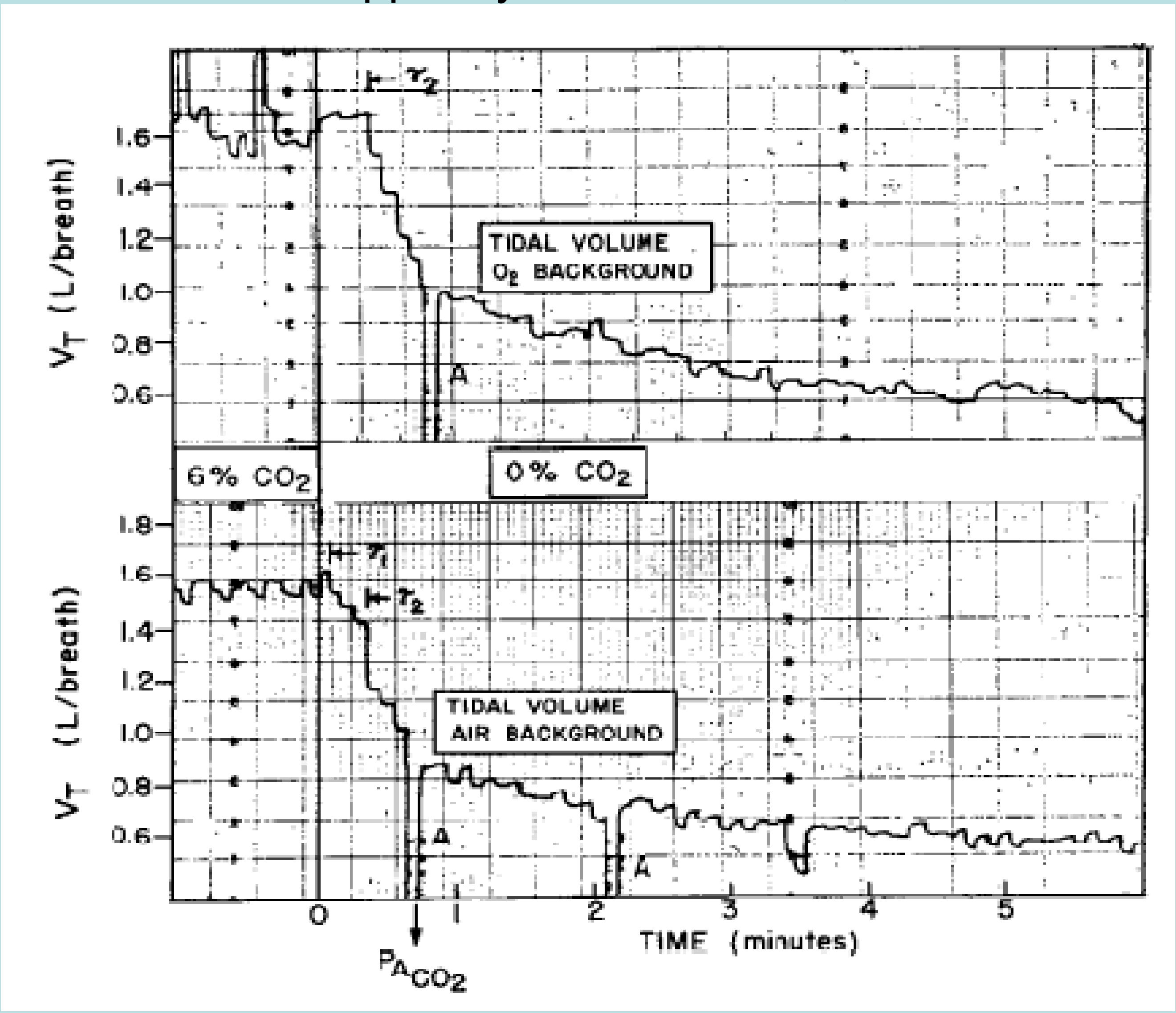
J Appl Physiol 16:473-484, 1961

FIG. 3

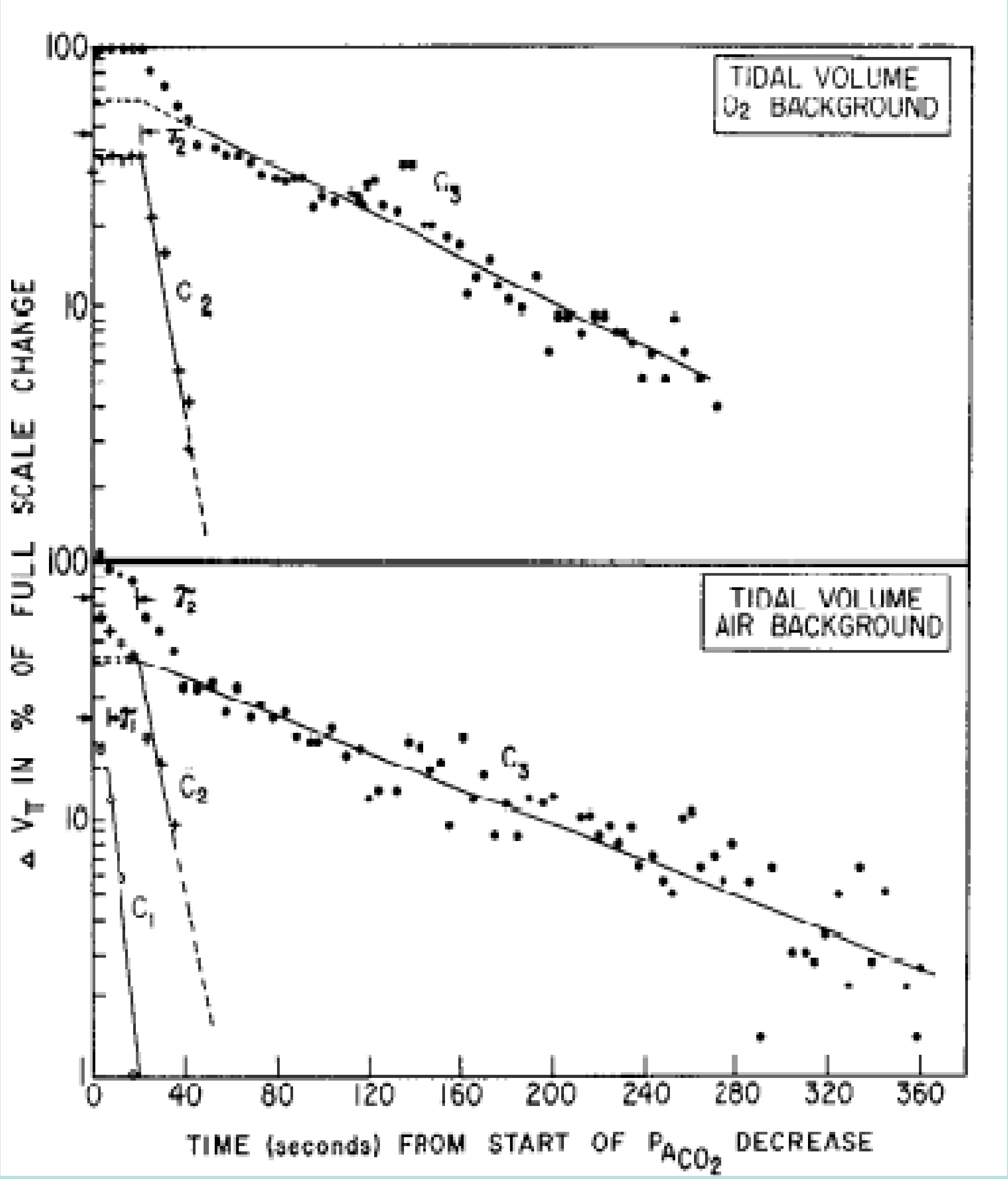


Tidal volume during “off-CO_2” transient in air and O_2 background

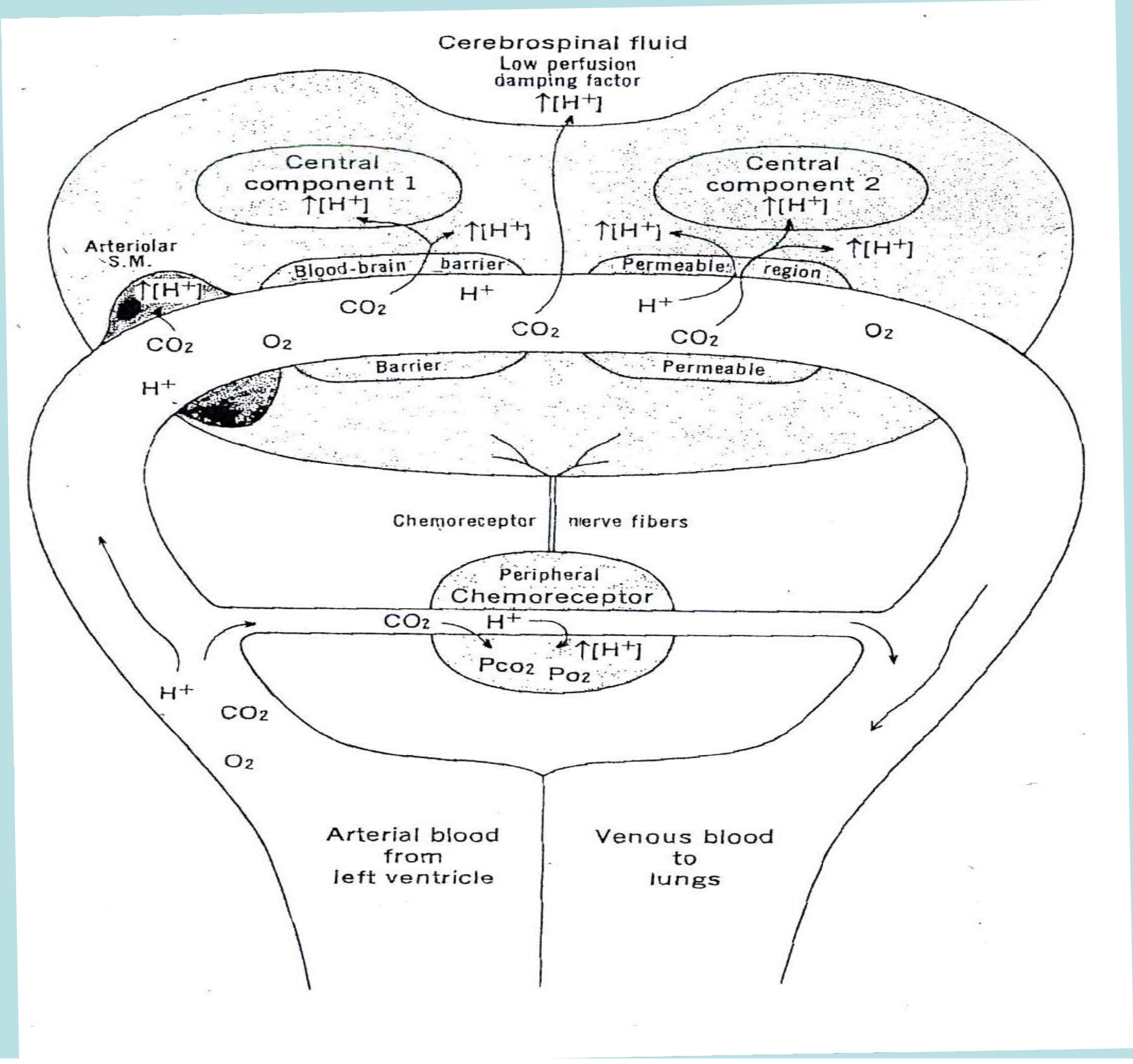
J Appl Physiol 35:903-913, 1973



Semilogarithmic plot of tidal volume data



Dual Center Concept of Respiratory Control



The Predictive Studies Series: Correlation of physiologic responses to extreme environmental stresses.

J. M. CLARK

Environmental Biomedical Stress Data Center, Institute for Environmental Medicine, University of Pennsylvania Medical Center, Room One, John Morgan Building, 36th Street and Hamilton Walk, Philadelphia, PA 19104-6068

UHM 31:33-51, 2004

THE PREDICTIVE STUDIES SERIES
DIVING, DECOMPRESSION, HYPEROXIA, HYPOXIA
Studies related to predictions of limiting physiologic effects in man of gases and pressure

PREDICTIVE STUDIES I (1969): TEKTITE I
A 60-day, open-sea exposure to normoxic N_2 at 43 FSW (2.3 ATA).
Collaborating sponsors: ONR, NASA, U. Penn, GE, Department of the Interior

PREDICTIVE STUDIES II (1970-1971)
A 14-day, continuous dry-chamber exposure to normoxic N_2 at 100 FSW (4 ATA).
Collaborating sponsors: U. Penn, NASA, Navy BUMED, ONR, NIH, Baylor U.

PREDICTIVE STUDIES III (1971-1973)
A 21-day, dry-chamber exposure to pressures ranging from 400 to 1200 FSW (12 - 37 ATA)
while breathing $He\text{-}O_2$, $N_2\text{-}O_2$, $Ne\text{-}O_2$ mixtures.
Collaborating sponsors: U. Penn, Navy BUMED, ONR, NASA, NIH, Union Carbide, Ocean Systems

PREDICTIVE STUDIES IV (1975)
Saturation - excursion series in phases of 0, 400, 800, 1200, and 1600 FSW. Exposure to normoxic He.
Physiologic studies and underwater work performance on oil wellhead.
Collaborating sponsors: U. Penn, Navy Medical R&D, ONR, NIH, NASA, Industry (offshore oil, gas, diving)

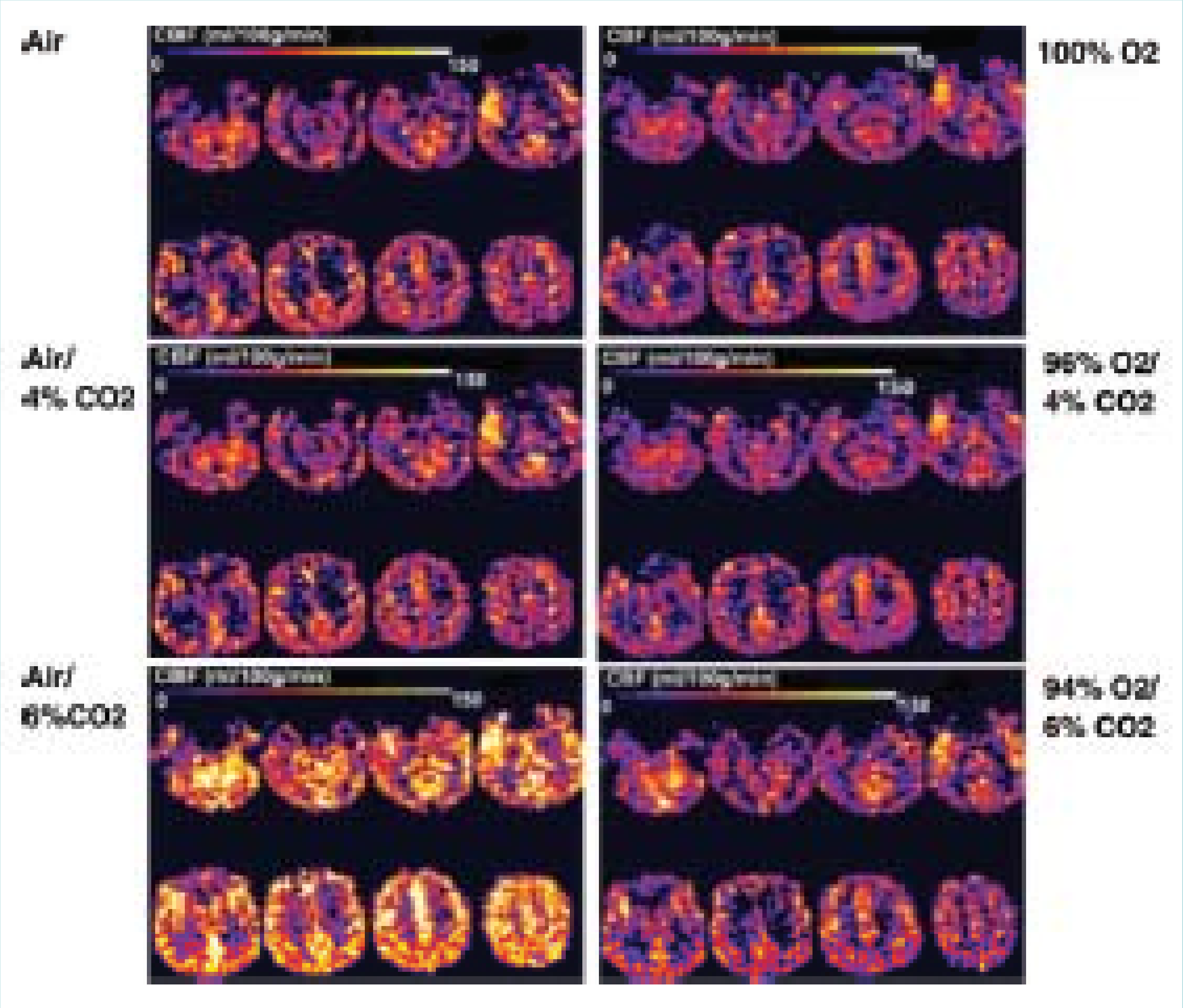
PREDICTIVE STUDIES V (1982-1987)
Definition of organ system O_2 tolerance - in relation to undersea activity, manned EVA, hyperoxic therapy,
and therapy of undersea and aerospace decompression accidents.
Collaborating sponsors: U. Penn, Navy Medical R&D, NOAA, NASA, Industry (offshore oil, gas)

PREDICTIVE STUDIES VI (1988-1992)
Extension of organ tolerance at normal and increased ambient pressure. Optimized intermittency.
Planning based on PS V - in relation to all oxygen uses.
Collaborating sponsors: U. Penn, Navy Medical R&D, NASA

PREDICTIVE STUDIES VII (1992-1997)
Interactions of hyperoxia, exercise, immersion, and CO_2 on brain oxygenation
and neurological O_2 tolerance.
Collaborating sponsors: U. Penn, ONR

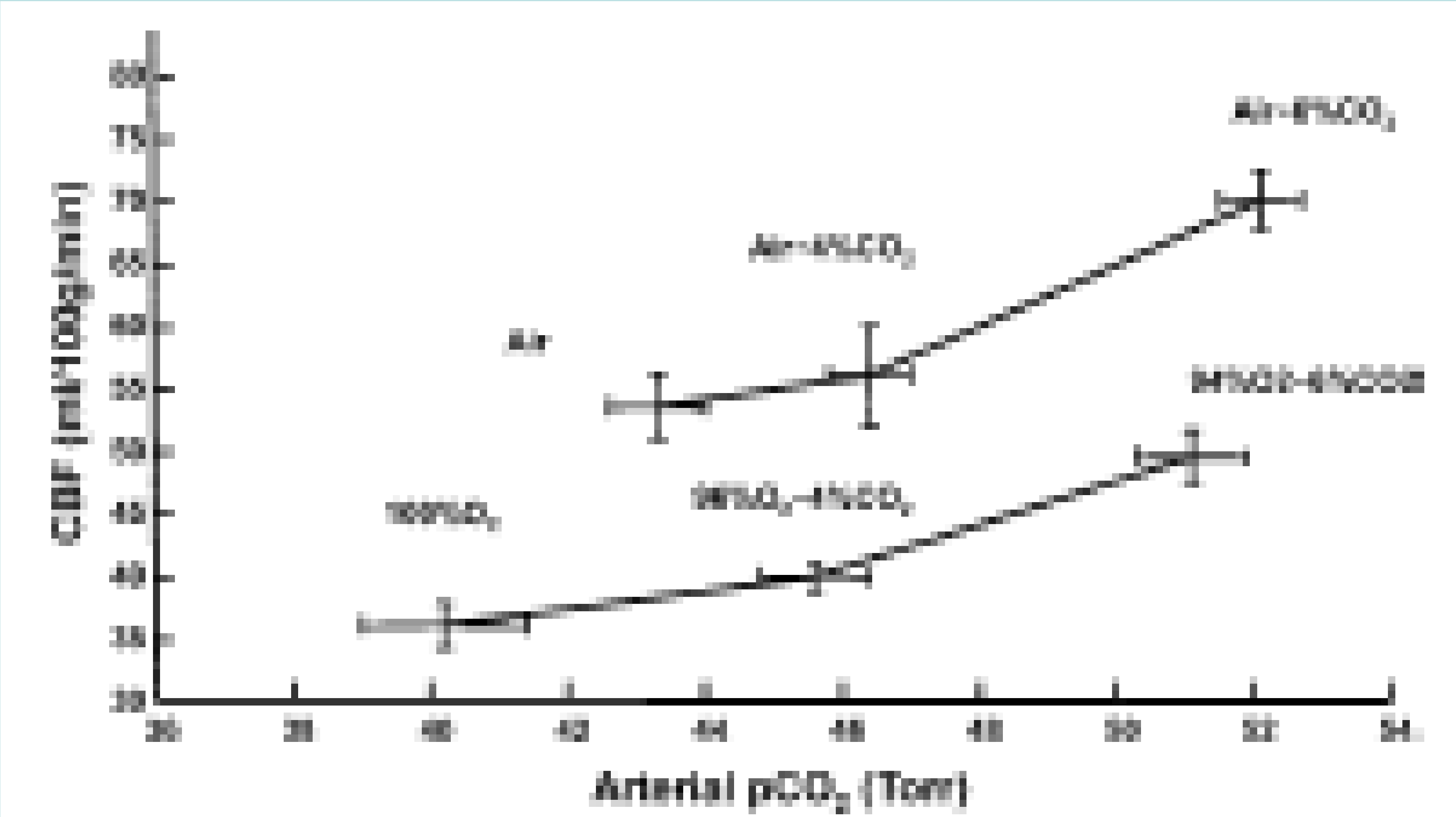
PREDICTIVE STUDIES VIII (1992-1997)
Influences of CO_2 on brain O_2 flow and respiratory control during hypoxia in work and at rest.
Collaborating sponsors: U. Penn, Navy Medical R&D, NASA

CASL-perfusion MRI images of CBF



CBF Responses to Arterial PCO_2 Changes in Air and O_2

J Appl Physiol 95:2453-2461, 2003



Tribute to the Extraordinary Life's Work of Dr. Christian .J. Lambertsen

Contributions and Influences on Diving and Aerospace Physiology and Operations

Dr. Michael Gernhardt

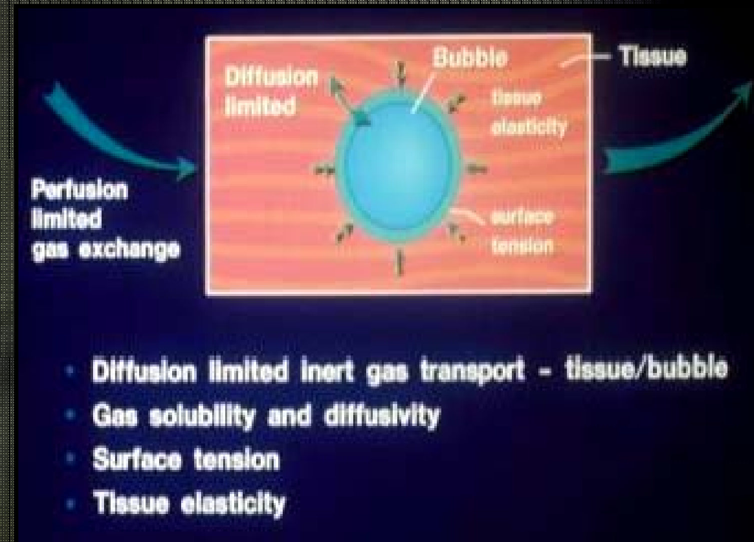
DECOMPRESSION TABLE DEVELOPMENT FOR COMMERCIAL DIVING

- One of Dr. Lambertsen's visions was to make the field the Laboratory. In the early 80's the right circumstances and people came together to make that happen.
- Our team generated a wide range of decompression tables and special procedures that had a major impact on the safety and efficiency of commercial diving.
  - Gen 1- Iteratively used the Tissue Bubble Dynamics Model (TBDM) with the Haldane workman model to develop Sur-D-O2 tables for single depth exposure-became the Oceaneering Tables
  - Gen 2- Multi-depth tables based on Iterative TBDM/Haldane Workman, including special multi-depth/multi gas schedules
  - Gen 3- British DOE funded development using the TBDM to generate a system of decompression tables covering air diving to extreme exposures- including variable depth on the same dive.


Order Paper

Tissue Bubble Dynamics Model (TBDM)- Provides Significant Prediction and Fit of Diving and Altitude DCS Data

- Decompression stress index based on tissue bubble growth dynamics *(Gernhardt, 1991)*
- *Diving: n*=6437 laboratory (430 DCS cases)
  - *Logistic Regression Analysis: $p < 0.01$*
  - *Hosmer-Lemeshow Goodness of Fit = 0.77*
- *Altitude: n=345 (57 DCS, 143 VGE)*
  - *Logistic Regression Analysis (DCS): $p < 0.01$*
  - *Logistic Regression Analysis (VGE): $p < 0.01$*
  - *Hosmer-Lemeshow Goodness of Fit (DCS): $p = 0.35$*
  - *Hosmer-Lemeshow Goodness of Fit (VGE): $p = 0.55$*



$$\frac{dR}{dt} = \frac{\frac{\alpha D}{h(r,t)}\left[P_a - vt + \frac{2\gamma}{r} + \frac{4}{3}\pi r^3 M - P_{Total} - P_{metabolic}\right] + \frac{rv}{3}}{P_a - vt + \frac{4\gamma}{3r} + \frac{8}{3}\pi r^3 M}$$

t = Time (sec)
a = Gas Solubility ((mL gas)/(mL tissue))
D = Diffusion Coefficient (cm^2/sec)
h(r,t) = Bubble Film Thickness (cm)
P_a = Initial Ambient Pressure (dyne/cm^2)
v = Ascent/Descent Rate (dyne/$cm^2 \cdot cm^3$)
g = Surface Tension (dyne/cm)
M = Tissue Modulus of Deformability (dyne/$cm^2 \cdot cm^3$)
P_{Total} = Total Inert Gas Tissue Tension (dyne/cm^2)
$P_{metabolic}$ = Total Metabolic Gas Tissue Tension

Gernhardt M.L. Development and Evaluation of a Decompression Stress Index Based on Tissue Bubble Dynamics. Ph.D dissertation. University of

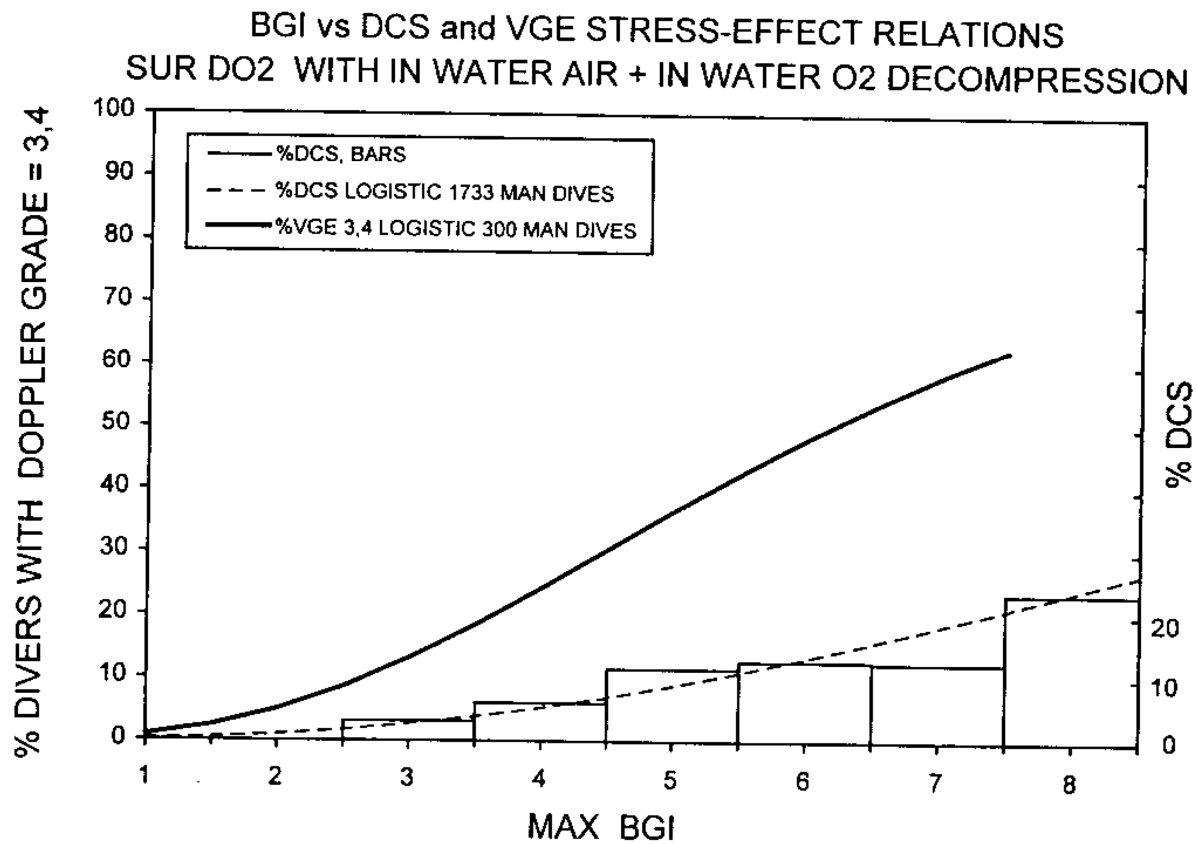
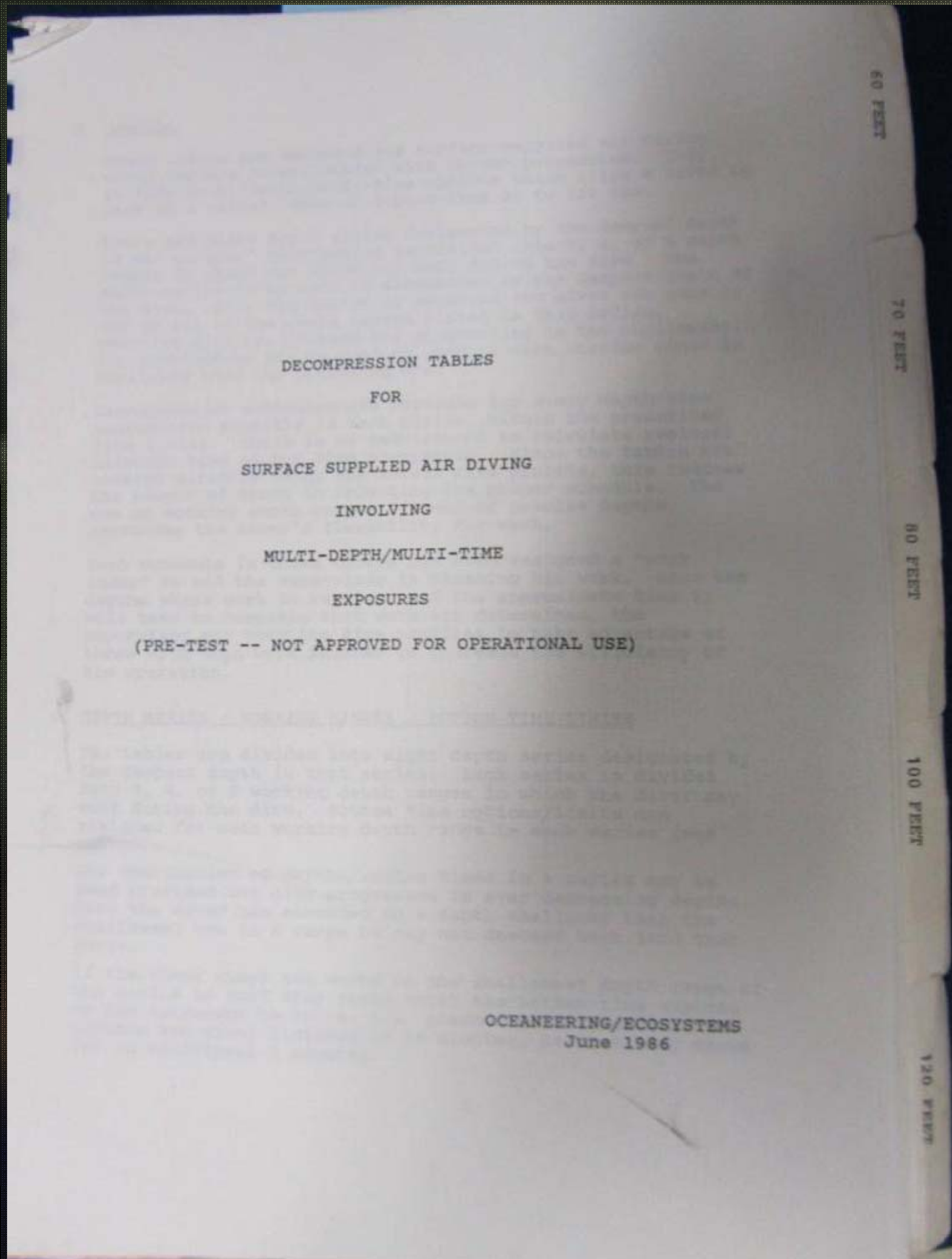


Fig. 9-4 TRIPLEX RELATION OF VGE, DCS, AND BUBBLE GROWTH INDEX: **AIR SUR DO_2 DIVING TRIALS** (DERIVED FROM LARGEST K-M VGE GRADE AT ANY SITE, AT REST OR WITH MOTION)

Regression of % VGE 3,4 and BGI (solid line) is derived from Figure 9-2, and regression of % DCS and BGI (dotted line and bars) is derived from Reference 39. Variations in performance of Air Sur DO_2 diving trials make stress analysis of this method less uniform than of standard air diving.

DEPTH SERIES / WORKING DEPTH RANGES / BOTTOM TIME OPTIONS-LIMITS

DEPTH SERIES	WORKING DEPTH RANGES (fsw) BOTTOM TIME OPTIONS/LIMITS (minutes)				
180	180-161 10 20 30	120-101 0 10 20 40	100-81 0 10 20 40	80-61 0 10 20 40	60-40 0 10 20 30 40 60
160	160-141 10 20 30 40	110-91 0 10 20 40	90-71 0 10 20 40	70-51 0 10 20 40 60	50-40 0 10 20 30 40 60
140	140-121 10 20 30 40 50	100-81 0 10 20 40 50	80-61 0 10 20 40 50	60-40 0 10 20 30 40 60	
120	120-101 10 20 30 40 50	90-71 0 10 20 40 60	70-51 0 10 20 40 60	50-30 0 10 20 30 40 60	



DECOMPRESSION TABLES

FOR

SURFACE SUPPLIED AIR DIVING

INVOLVING

MULTI-DEPTH/MULTI-TIME

EXPOSURES

(PRE-TEST -- NOT APPROVED FOR OPERATIONAL USE)

OCEANEERING/ECOSYSTEMS
June 1986

DEPTH SERIES 180

WORKING DEPTH RANGES: 180-161 120-101 100-81 80-61 60-40

SCHED ID	WORK PHASE — DEPTH RANGES (fsw) 180-161	120-101	100-81	80-61	60-40	WATER DECOMPRESSION ON AIR — DEPTH (fsw) 60	50	40	30	SUR INT	CHAMBER DECOMPRESSION ON OXYGEN — DEPTH (fsw) 50	40	WORK INDEX
	TIME (min)					TIME (min)				(min)	TIME (min)		
22040	20	20	0	40	0				16	5	10	39	.9
22041	20	20	0	40	10				12	5	10	43	1.0
22042	20	20	0	40	20				9	5	10	46	1.2
22043	20	20	0	40	30				6	5	10	50	1.3
22044	20	20	0	40	40				4	5	10	53	1.4
22046	20	20	0	40	60				0	5	10	60	1.5
22100	20	20	10	0	0				18	5	10	24	.7
22101	20	20	10	0	10				14	5	10	27	.8
22102	20	20	10	0	20				11	5	10	30	1.0
22103	20	20	10	0	30				8	5	10	34	1.1
22104	20	20	10	0	40				5	5	10	38	1.2
22106	20	20	10	0	60				1	5	10	45	1.4
22110	20	20	10	10	0				18	5	10	29	.8
22111	20	20	10	10	10				14	5	10	32	.9
22112	20	20	10	10	20				11	5	10	36	1.0
22113	20	20	10	10	30				8	5	10	40	1.1
22114	20	20	10	10	40				5	5	10	44	1.2
22116	20	20	10	10	60				1	5	10	51	1.4
22120	20	20	10	20	0				18	5	10	35	.8
22121	20	20	10	20	10				14	5	10	39	1.0
22122	20	20	10	20	20				11	5	10	42	1.1
22123	20	20	10	20	30				8	5	10	46	1.2
22124	20	20	10	20	40				5	5	10	50	1.3
22126	20	20	10	20	60				1	5	10	56	1.5
22140	20	20	10	40	0				18	5	10	47	.9
22141	20	20	10	40	10				14	5	10	50	1.1
22142	20	20	10	40	20				11	5	10	54	1.1
22143	20	20	10	40	30				8	5	10	57	1.2
22144	20	20	10	40	40				5	5	10	61	1.3
22146	20	20	10	40	60				1	5	10	70	1.5

ASCENT RATES:		
25 FPM between levels and to first water stop	10 FPM between stops; 30 FPM from last water stop to surface	50-40 10 minutes on oxygen (1FPM); 40-0 10 minutes on oxygen (4FPM)

ASCENT TIME NOT INCLUDED IN STOP TIME

Exposure Phase

180'/20 min, 120'/20 min
100'/10 min
60'/0 min
Table # 22110

Decompression Phase

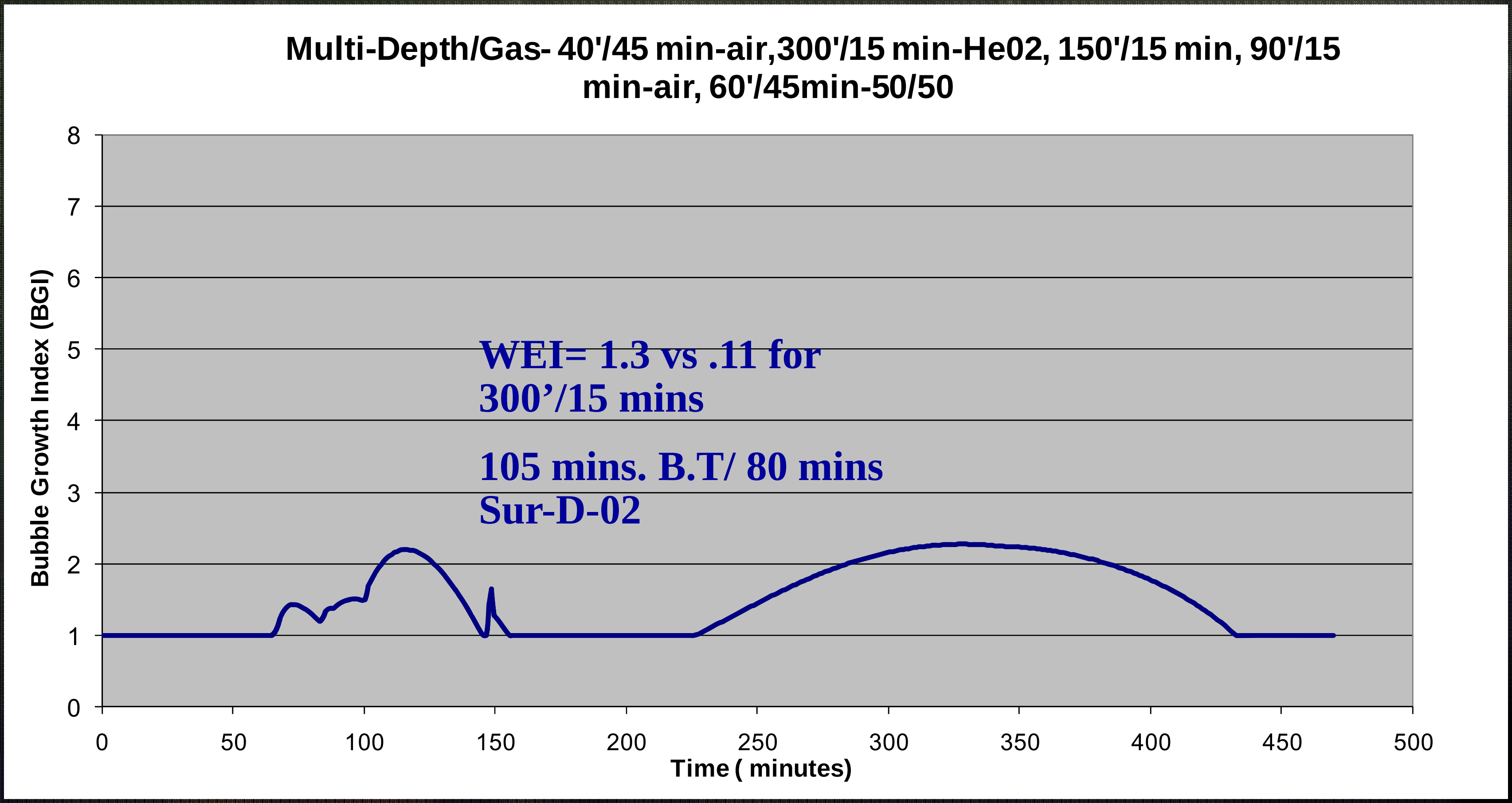
30'/18mins in water-air,
followed by 10 min at 50'/O_2,
10 min 50-40'/O_2,
followed by 29 min 40'-0_2,
followed by 40-0' -30 min O_2

Multi-Depth / Multi-Gas Decompressions

Table 6. Typical Multi-depth/Multi-gas

Depth (FSW)	Time (Minutes)	GAS
30-40	60-120	Air
240-300	15-40	He 0_2 (10-14%)
180	15- 40	He 0_2
100- 80	15- 40	Air
60-30	30-45	Air or 50/50 Nitrox

300 FSW - 40'/45 min-air,300'/15 min-HeO$_2$, 150'/15 min – HeO$_2$, 90'/15 min-air, 60'/45min-50/50



Comparison of Work Efficiency Index (WEI)

Dive Type	Depth Range (FSW)	Work Efficiency Index (WEI)
SUR-D-0_2 (Single Depth)	70-170	.5-.65
Repet Up	40-190	.8-1.0
Multi-Depth SUR-D-0_2	30-190	1.75- 2.0
$He0_2$ SUR-D-0_2	200-300	.1- .4
Multi-Depth Multi-Gas	30-300	1.0 -3.5
Saturation	300 FSW	3-10 (10-30 Days)
Air Saturation Aquarius	50 FSW	3.8-4.7

WEI = Bottom time /decompression time

North Sea DCS Incidence as a Function of Time and Depth

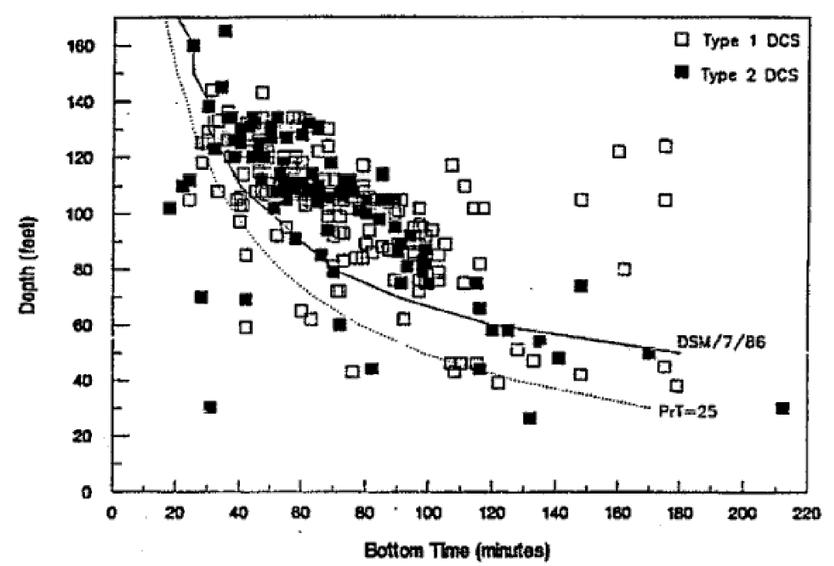


Figure 3.1 - Distribution of DCS incidents associated with North Sea commercial diving operations. (from (161)). The solid curve denotes the time/depth restrictions imposed by the Department of Energy Diving Safety Memorandum (DSM7). The dotted curve shows the time/depth limits associated with a Hempleman Prt index - 25 (in units of ata - minutes). The squares denote cases of DCS.

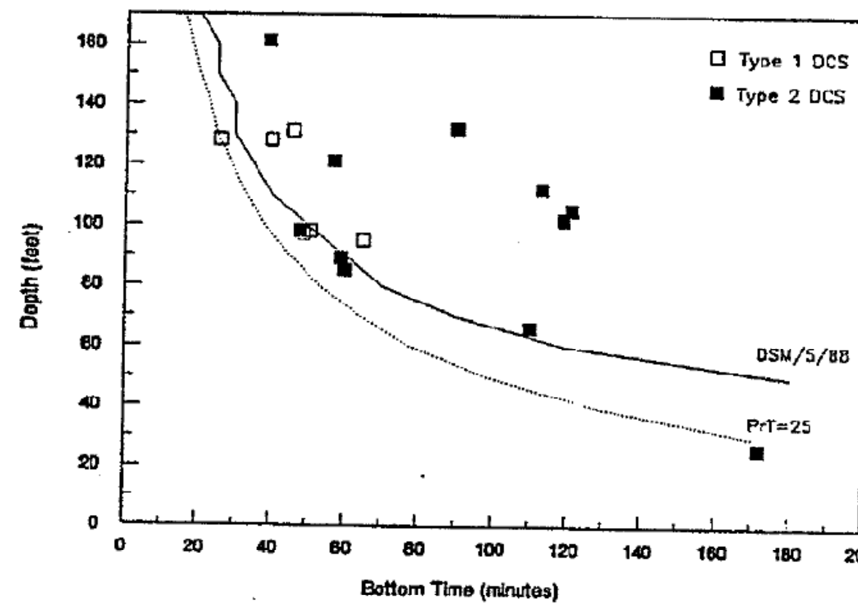


Figure 3.2 - DCS incidents in 1988 after implementation of time/depth restrictions (DSM5). (from (161)) The majority of the incidents of DCS occurred at exposure times and depths that exceeded the DSM5 limits (≈Prt=30). There was only one case of DCS below Prt=25.

- The British Department of energy restricted time/depth exposure to Hempleman PrT < 25 (atmosphere-minutes)
    - constrained Haldane/Workman tables to within “safe” exposure limits
- Reduced both DCS incidence and diving efficiency
- Diving companies modified Sur-D-02 tables more water stops/more chamber 02- made no difference

Laboratory Trials of Bubble Dynamics Tables

Table 4. Sub sea International Laboratory Trials

Profile FSW/min	n	DCS	V.G.E. (Grade 3, 4)
90/80	**6**	**0**	**0**
120/40	**6**	**0**	**1-Grade 4**
130/40	**3**	**0**	**0**
150/40	**9**	**0**	**3=Grade 3**
Total	24	0	4(16%)

Trials conducted at Sub Sea International (New Orleans)

Informed consenting commercial divers

Wet Pot, representative tasks, water temperature, wet suits, Doppler VGE

Phased Approach: laboratory trials, sea trials with time/depth recording and Doppler, probationary period of increasing exposures, modification, release for routine operations

Bubble Dynamics Tables – Summary of Operational Results

Phase	Decompression Procedure	Offshore Dives	DCS Incidents	DCS %
III	*No Decompression*	20,000	0	0%
III 1993-5	Air SUR-D 0_2 With N_2-0_2	4,000 500	9	.2%
IV (ops)	Air SUR-D-0_2 & Multi-Depth	2,500	1	.04%

•The decompression dives had bottom times well over conventional exposure limits (“triple z” repet group and extreme exposure)

•Final operational tables incorporating some reductions in bottom time (still well over “z” repet group

•Much Deeper in -water stops (last stop at 60 fsw vs. 30 fsw), staged chamber 02- 50-30 feet, slower ascent rates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NASA
24
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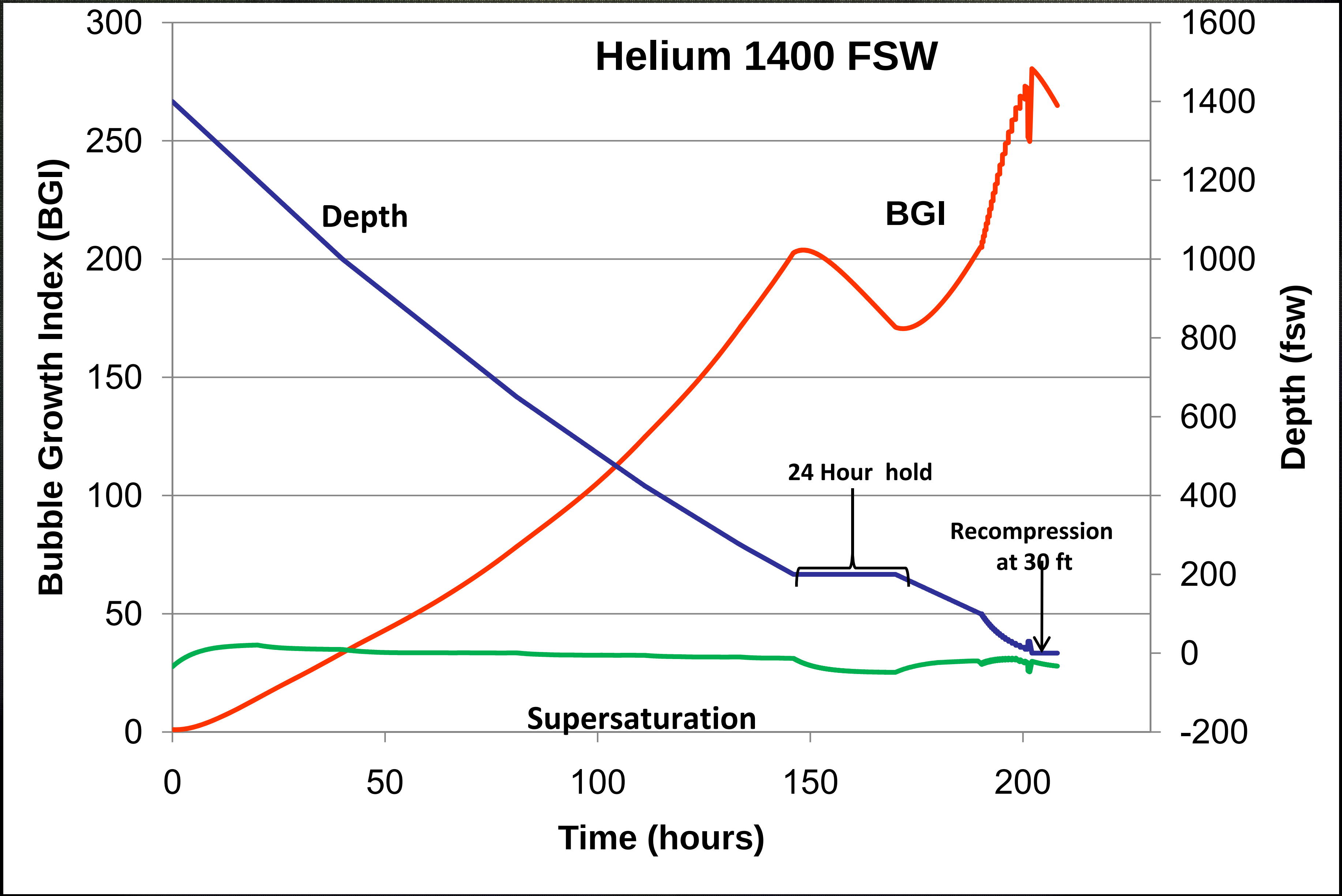
Predictive Studies IV – Saturation Decompression



Intermittent Recompression Technique

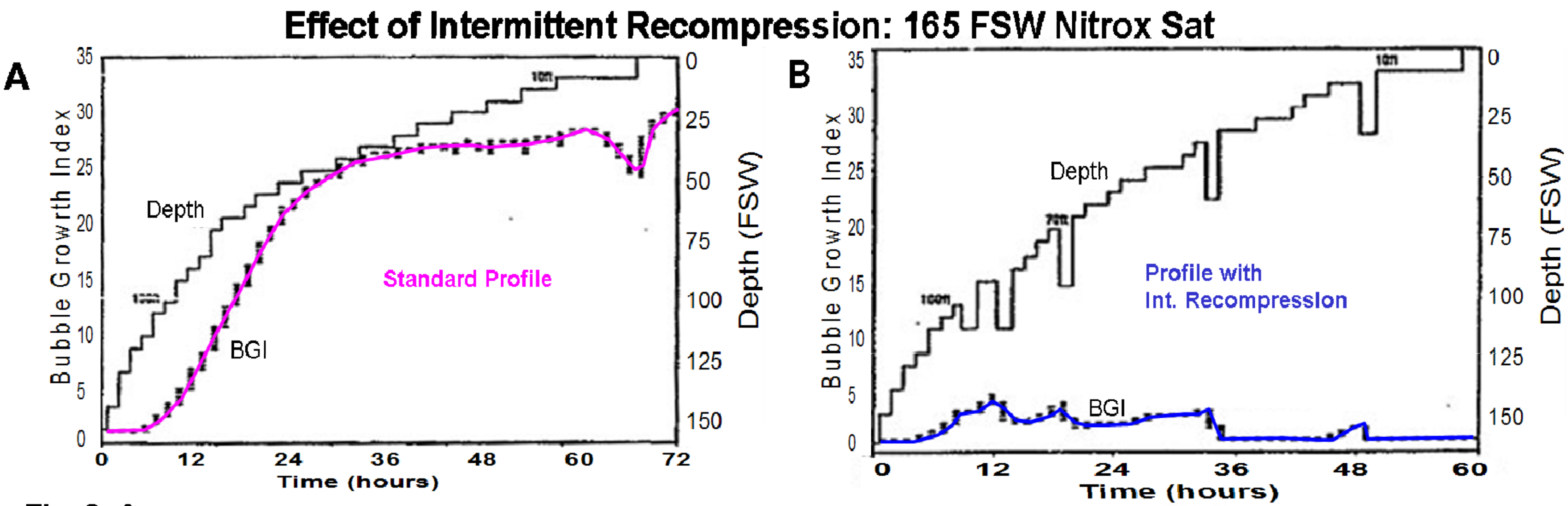


Fig. 3. A: 165 FSW saturation on Nitrox, decompressed to 45 FSW using an experimental staged protocol (ppO_2=0.5 ATA), then switched to air for remaining decompression. 50% DCS (n=10) observed with the 4000 minute protocol (7). Protocol modified to 7000 minutes (4.86 days) for operations.

B: Same decompression protocol as in A, but modified to include intermittent recompression (without exercise) achieves a faster ascent time (2.43 days) with lower decompression stress (Bubble Growth Index, or BGI), demonstrating the theoretical advantage of intermittent recompression.

$$\frac{dR}{dt} = \frac{\dfrac{\alpha D}{h(r,t)}\left[P_a - vt + \dfrac{2\gamma}{r} + \dfrac{4}{3}\pi r^3 M - P_{Total} - P_{metabolic}\right] + \dfrac{rv}{3}}{P_a - vt + \dfrac{4\gamma}{3r} + \dfrac{8}{3}\pi r^3 M}$$

r = Bubble Radius (cm)
t = Time (sec)
a = Gas Solubility ((mL gas)/(mL tissue)
D = Diffusion Coefficient (cm^2/sec)
h(r,t) = Bubble Film Thickness (cm)
P_a = Initial Ambient Pressure ($dyne/cm^2$)
v = Ascent/Descent Rate ($dyne/cm^2 \cdot cm^3$)
g = Surface Tension (dyne/cm)
M = Tissue Modulus of Deformability ($dyne/cm^2 \cdot cm^3$)
P_{Total} = Total Inert Gas Tissue Tension ($dyne/cm^2$)
$P_{metabolic}$ = Total Metabolic Gas Tissue Tension

Altitude: n=345 (57 DCS, 143 VGE)
- Logistic Regression Analysis (DCS): $p < 0.01$
- Logistic Regression Analysis (VGE): $p < 0.01$
- Hosmer-Lemeshow Goodness of Fit (DCS): p = 0.35
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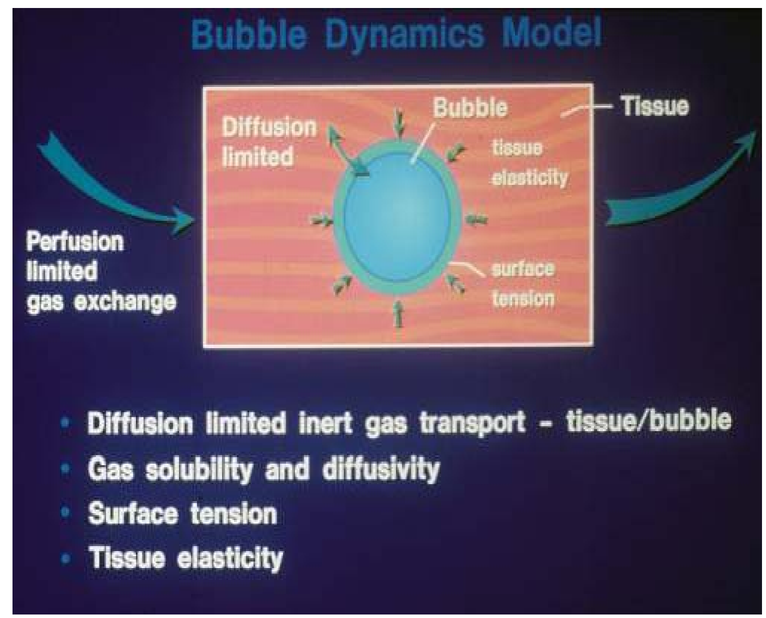
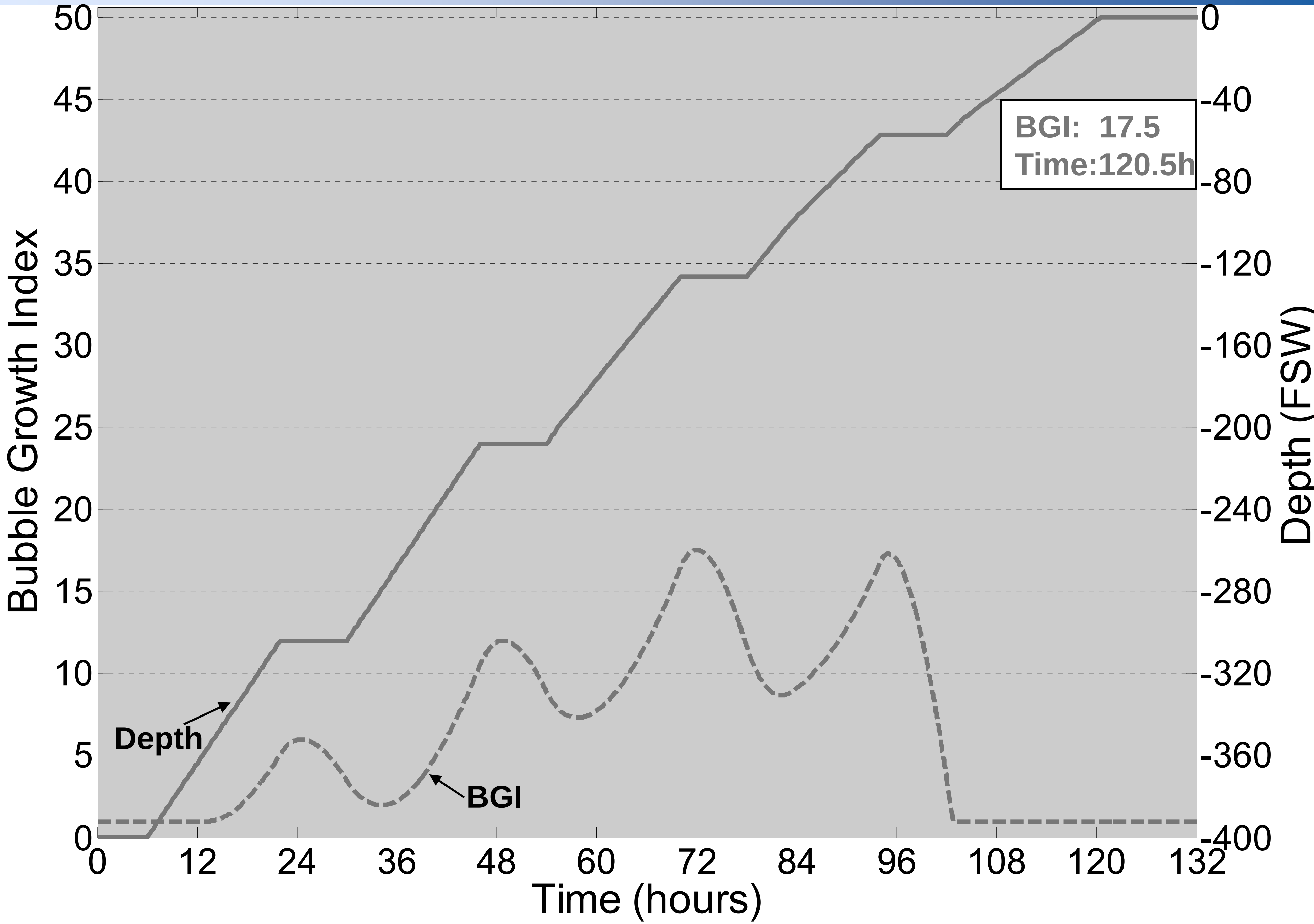
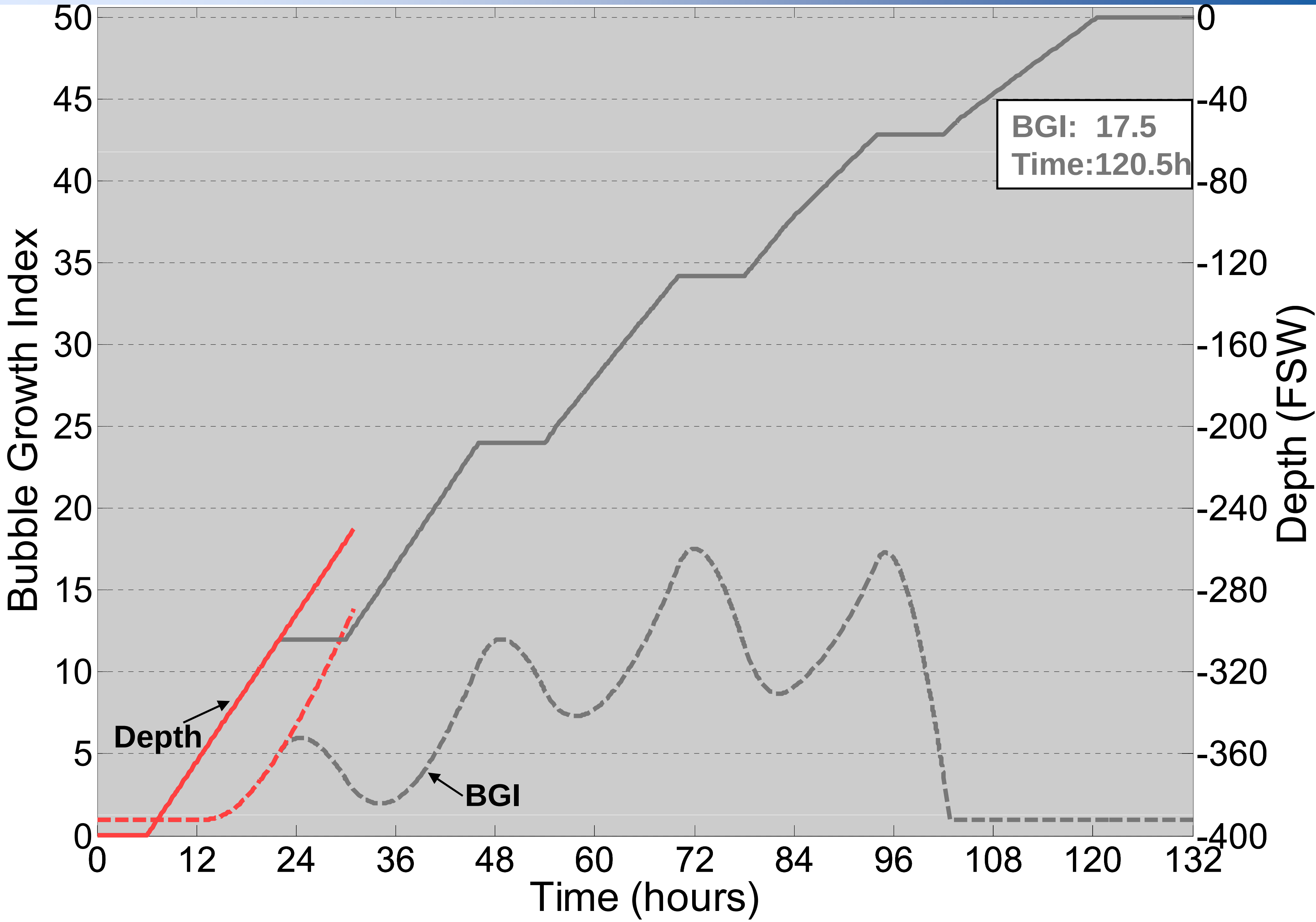


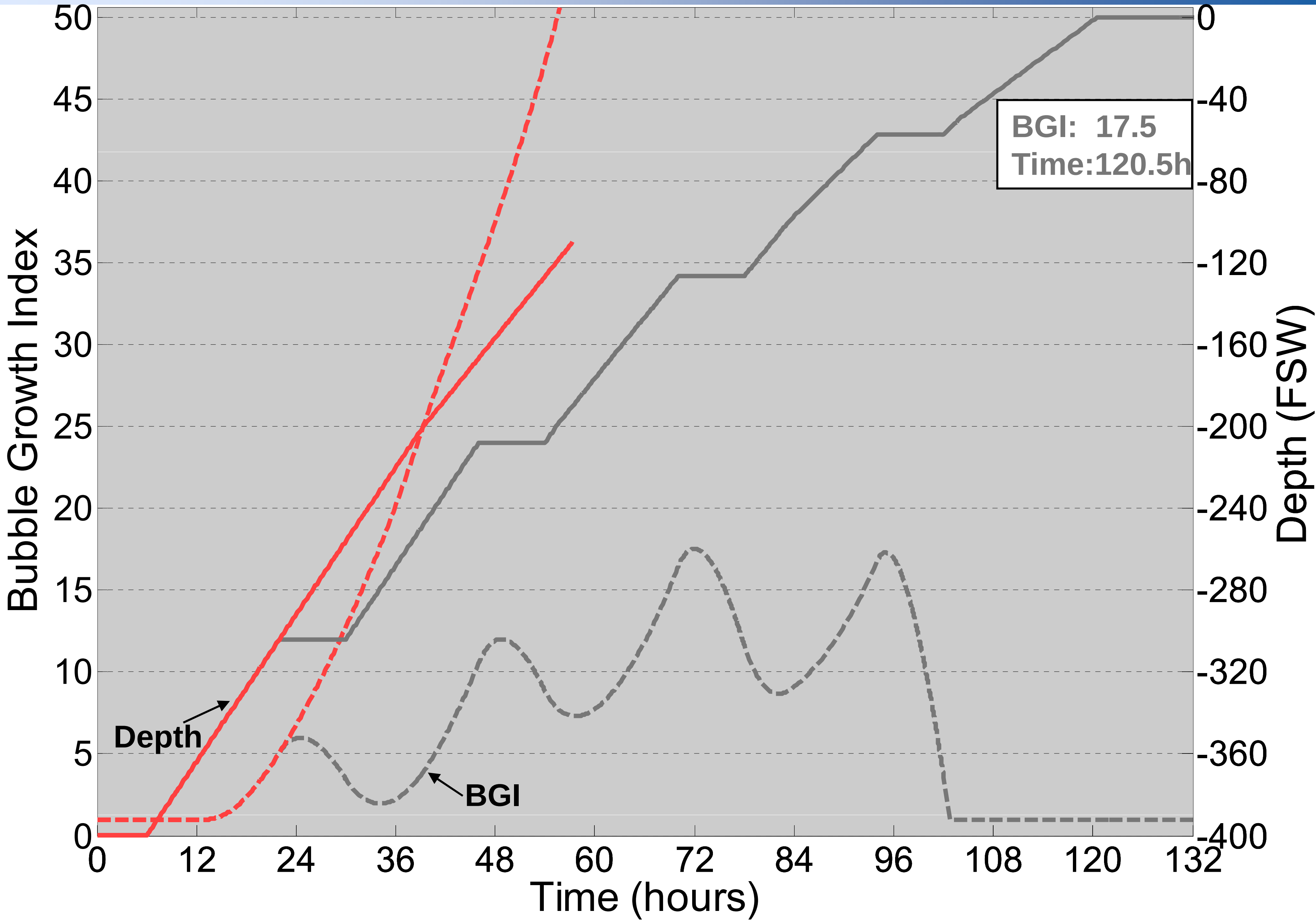
USN 400 FSW Heliox Sat Decompression Profile



USN Profile *vs.* USN Profile Without 8 hr Holds



USN Profile *vs.* USN Profile Without 8 hr Holds



Multi-Center Study: NASA, Duke, DCIEM, Hermann UT

Exercise 10 min @ 75% $V02_{peak}$
And/or light exercise (160-253 Kcal/hr)

2hr oxygen prebreathe

Micro-gravity simulation
(non-ambulation)

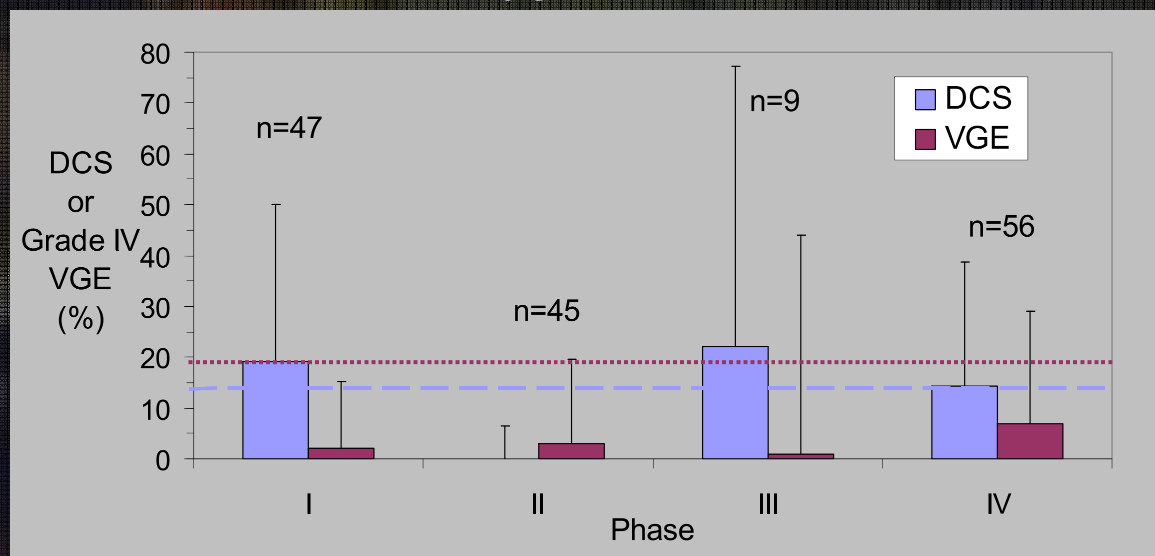
Simulated EVA exposure at
4.3 psi 4 hrs

Use of “Suit Simulator” for
EVA Exercise

Prebreathe Trials

Phase I	Rest	10 min 75% $VO_{2\ peak}$	4 hr EVA Simulation	DCS 19%
Phase II	Rest	10 min 75% $VO_{2\ peak}$, 40 min Light Activity	4 hr EVA Simulation	0%
Phase III	Rest	40 min Light Activity	4 hr EVA Simulation	22%
Phase IV	Rest	95 min Light Activity	4 hr EVA Simulation	14%

PRP Phase I-IV 2 hr oxygen prebreathe exercise protocols



- High intensity exercise (75% peak oxygen consumption [$VO_{2\ peak}$])
- Low intensity activity (5.8 $mL \cdot kg^{-1} \cdot min^{-1}$ VO_2)
- Neither High or low intensity exercise was acceptable
- Coupling High with low intensity exercise was acceptable

DCS and Grade IV VGE observations (shown with 95% upper confidence limit bars dashed lines indicating accept levels for DCS and VGE incidences)

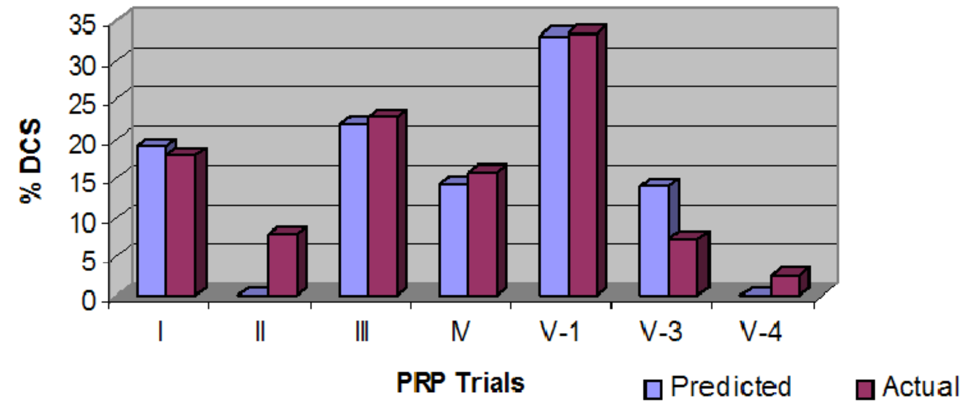
Tissue Bubble Dynamics Model (TBDM)

Data Set: In-Water Decompression on Air		Test for Improvement		Test for Goodness of Fit	
Index	Log-Likelihood	x^2	p-value	x^2	p-value/ df
Null set	-529	n/a	n/a	n/a	n/a
Bubble Growth Index	**-498**	**62.8**	**<0.001**	**4.8**	**0.77/8**
Relative Super-saturation	-524	10.8	.001	19.4	0.08/12
Exposure Index	-505	47.9	<0.001	30.5	0.00/9

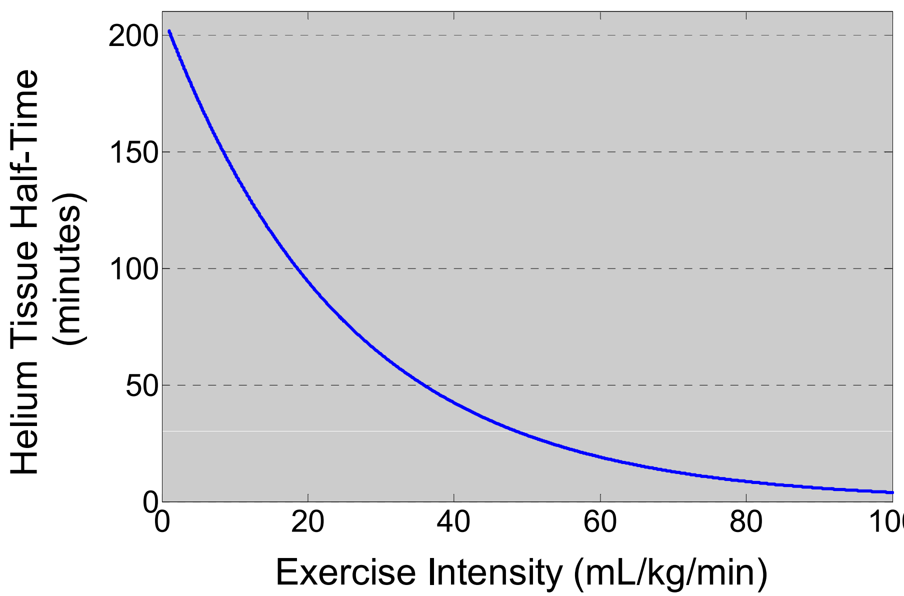
Significant prediction ($p < 0.001$) and goodness of fit (Hosmer-Lemeshow: p=.77) with 430 cases of DCS in 6437 laboratory dives for TBDM. **Used operationally in over 25,000 dives**

- TBDM used in conjunction with NEPM that relates tissue inert gas exchange rate constants to exercise (mL O_2/kg-min), to develop decompression schedules from saturation at depths from 45 feet sea water (FSW) to 400 FSW.

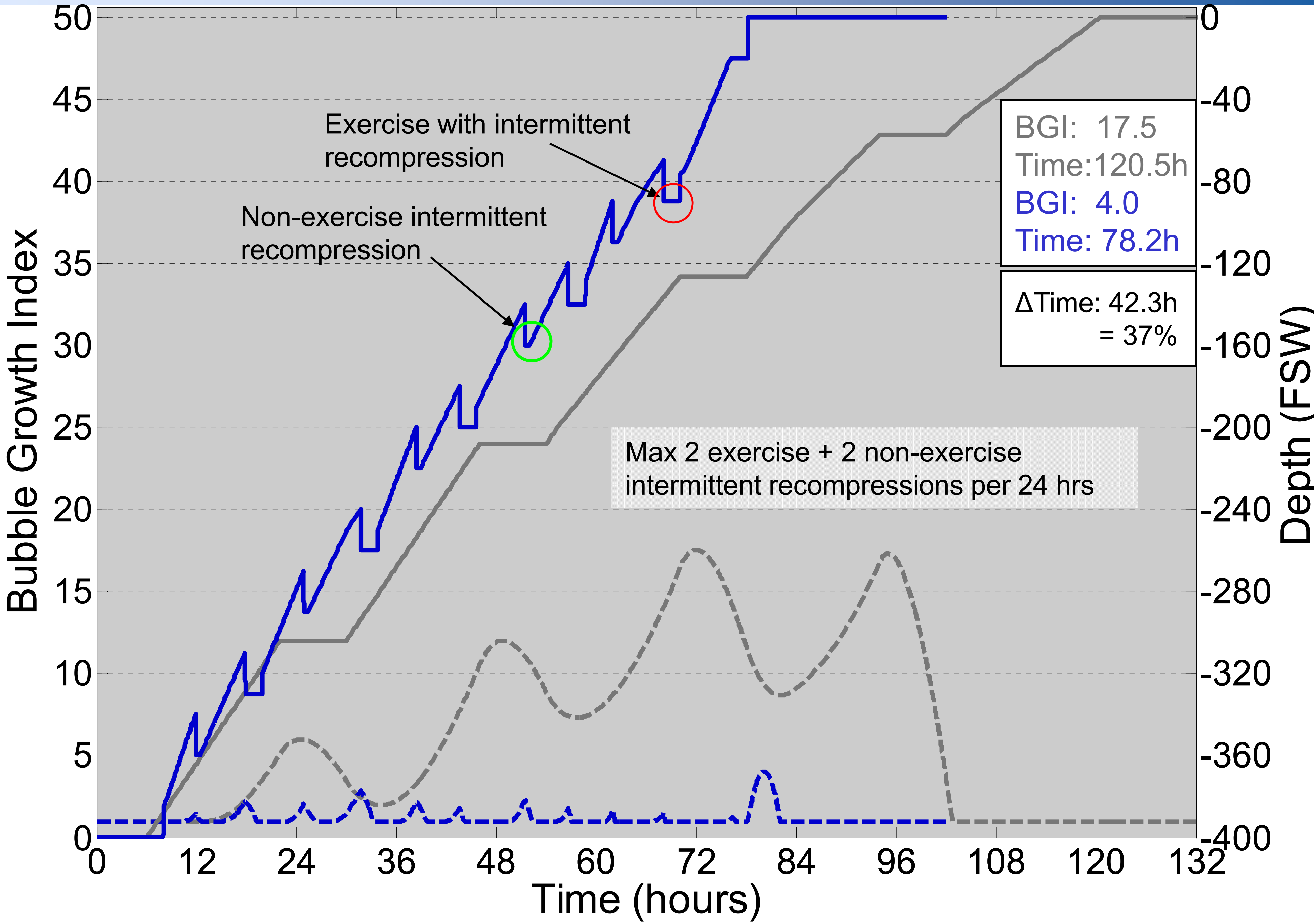
NASA Exercise Prebreathe Model (NEPM)



Significant prediction ($p < 0.001$) and goodness of fit (Hosmer-Lemeshow: p=.70) with 22 cases of DCS in 159 altitude exposures for NEPM (Hosmer-Lemeshow p=.70). **Used operationally in over 40 spacewalks**

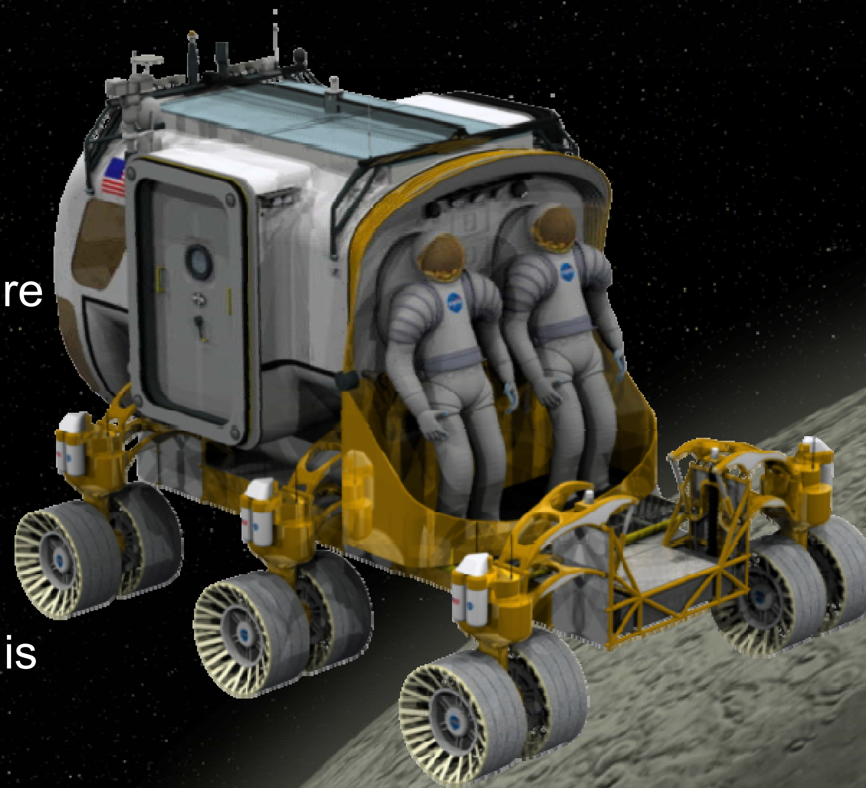


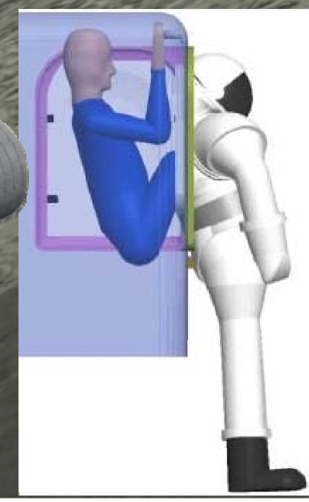
USN Profile vs. Intermittent Recompression + Exercise Countermeasures (IRECM)

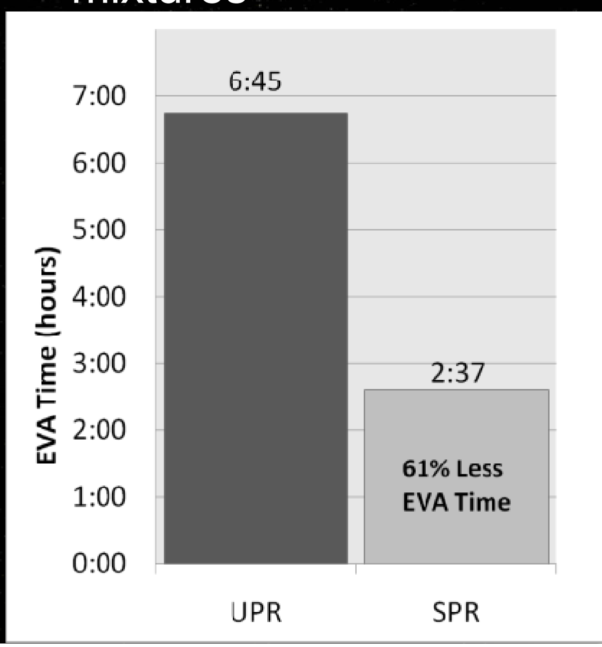


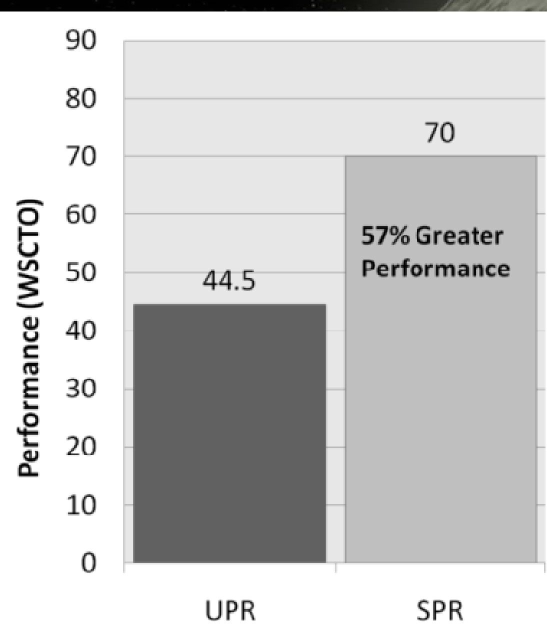
Background: Lunar Electric Rover

- Current plans for lunar surface exploration include small pressurized rovers ("Lunar Electric Rovers") that are quickly ingressed and egressed with minimal consumables losses
  - Cabin: 8 PSI, 32% O_2, 68% N_2
- The capability for crew members to perform multiple short extravehicular activities (EVAs) at different locations is enabled by a combination of variable pressure EVA suits, intermittent recompression, and Nitrox breathing mixtures



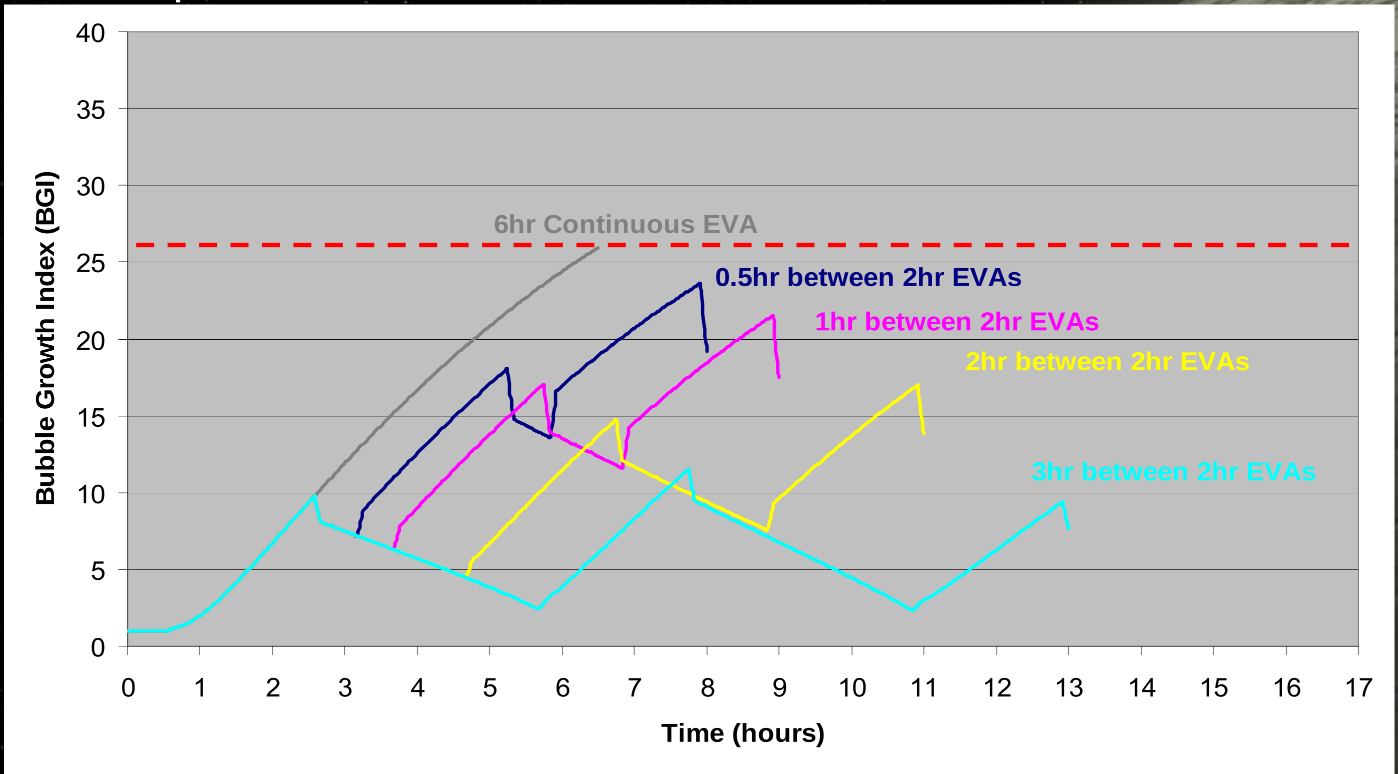




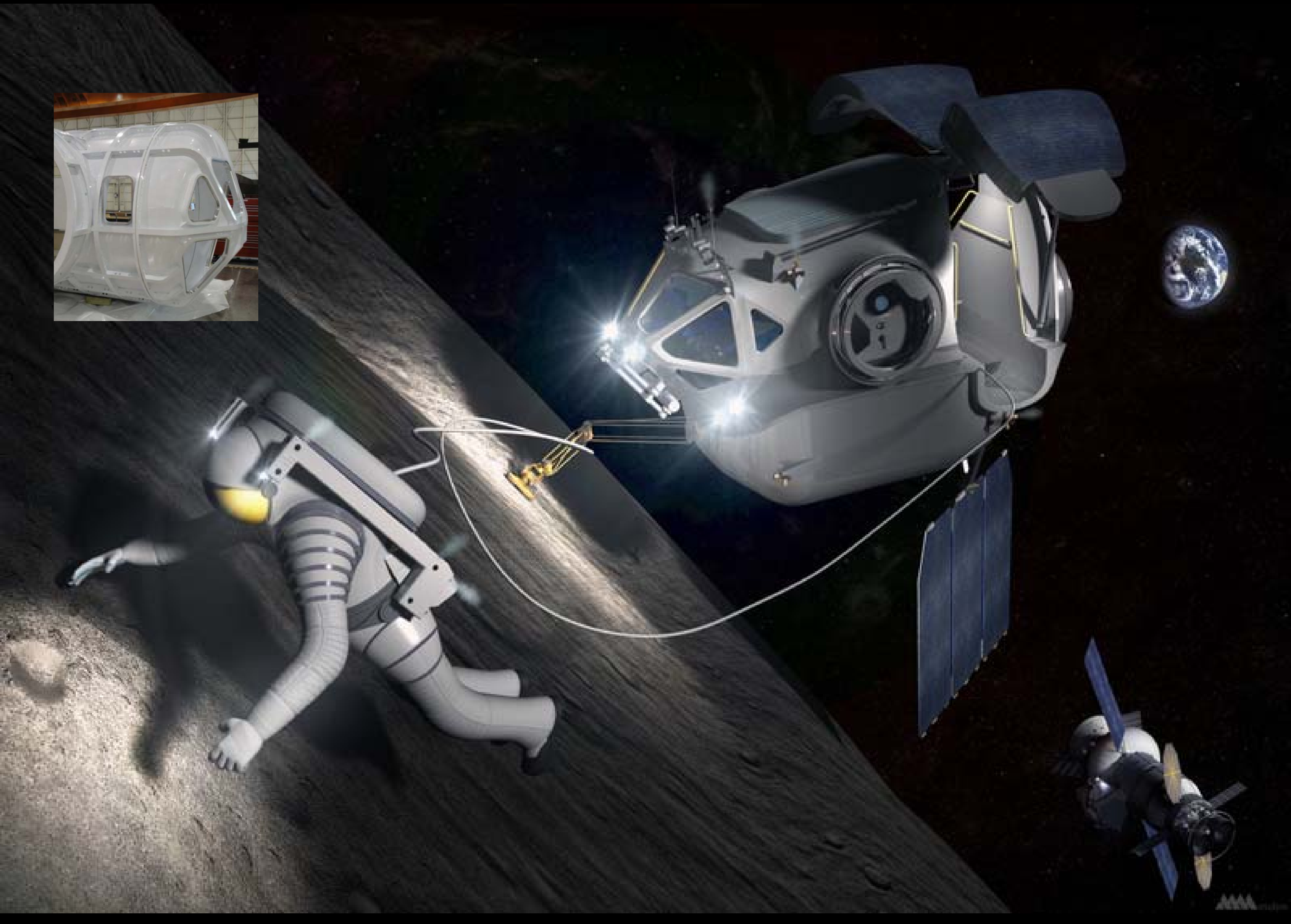


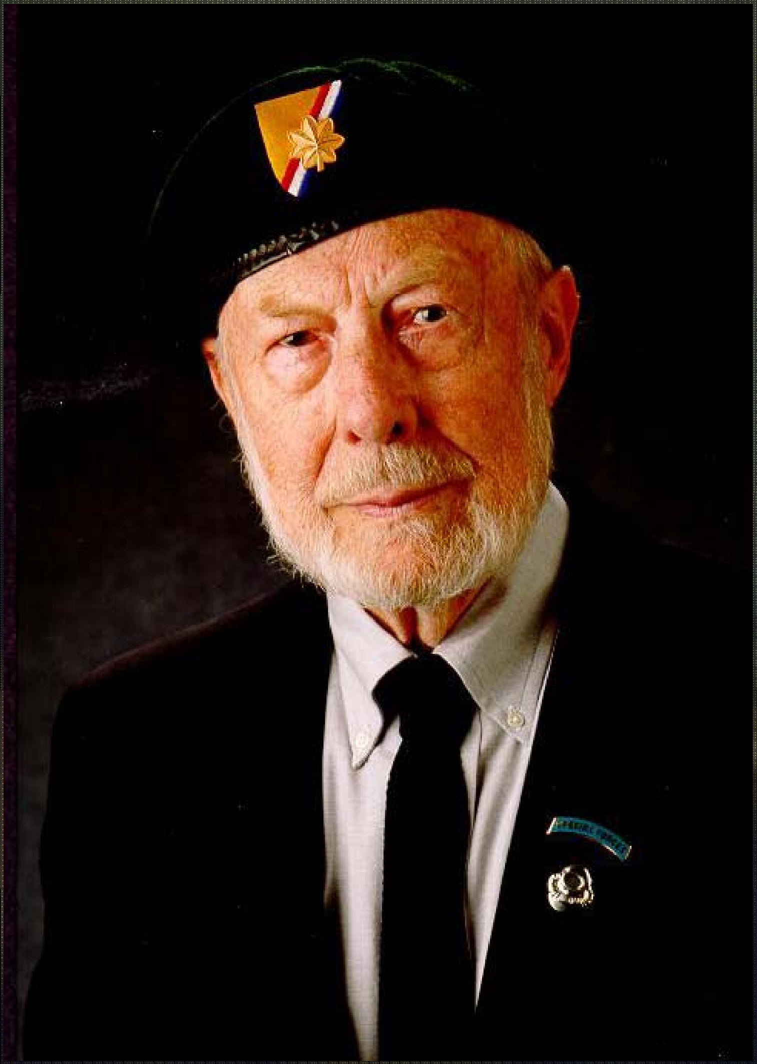
Background: Intermittent Recompression

- Intermittent Recompressions (IR) during saturation decompression previously proposed as a method for decreasing decompression stress and time *(Gernhardt,1988)*
  - Gas bubbles respond to changes in hydrostatic pressure on a time scale much faster than the tissues
- Previous modeling work and empirical human and animal data indicate that IR between EVA suit pressure (≤4.3 psia, 100% O_2) and cabin pressure (8 psia, 32% O_2) may reduce decompression stress

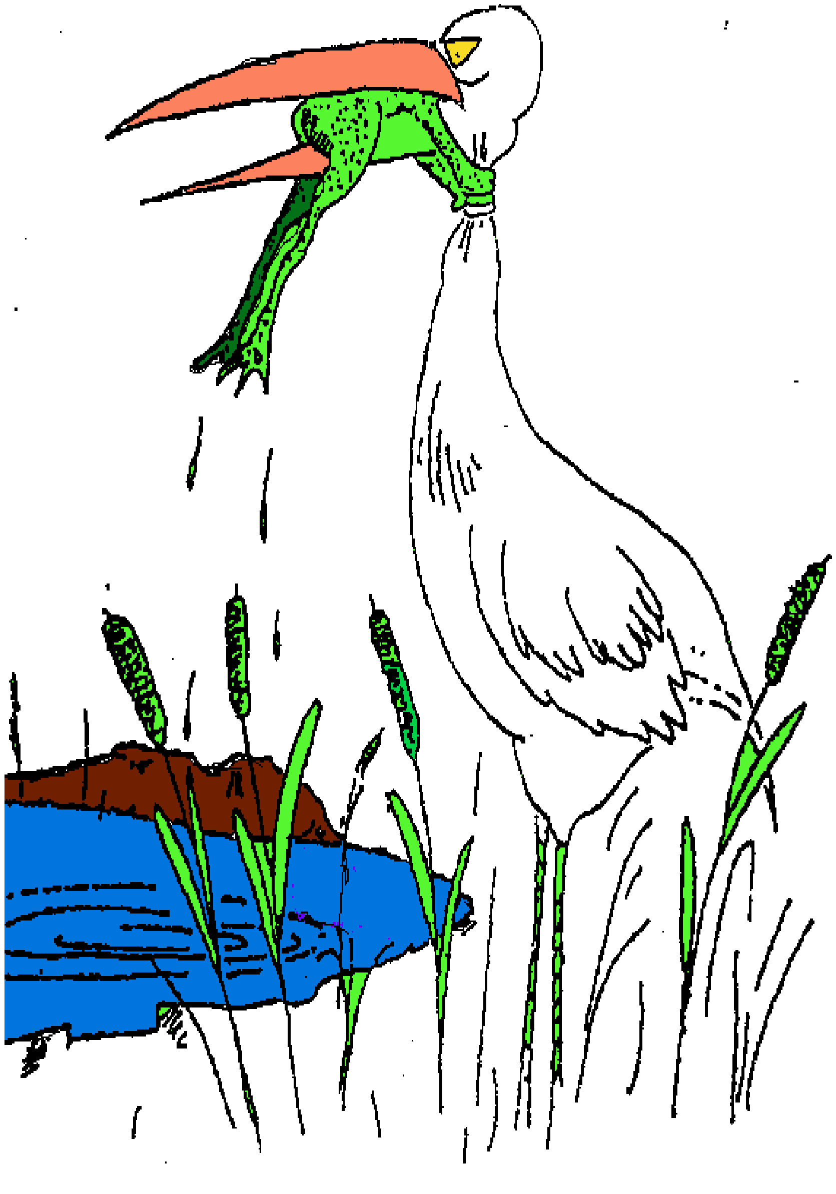


- IR has been shown to decrease decompression stress in humans and animals *(Pilmanis et al. 2002, Møllerløkken et al. 2007)*





Farewell Chris, you will be missed but live on in so many ways.



Never Give Up!