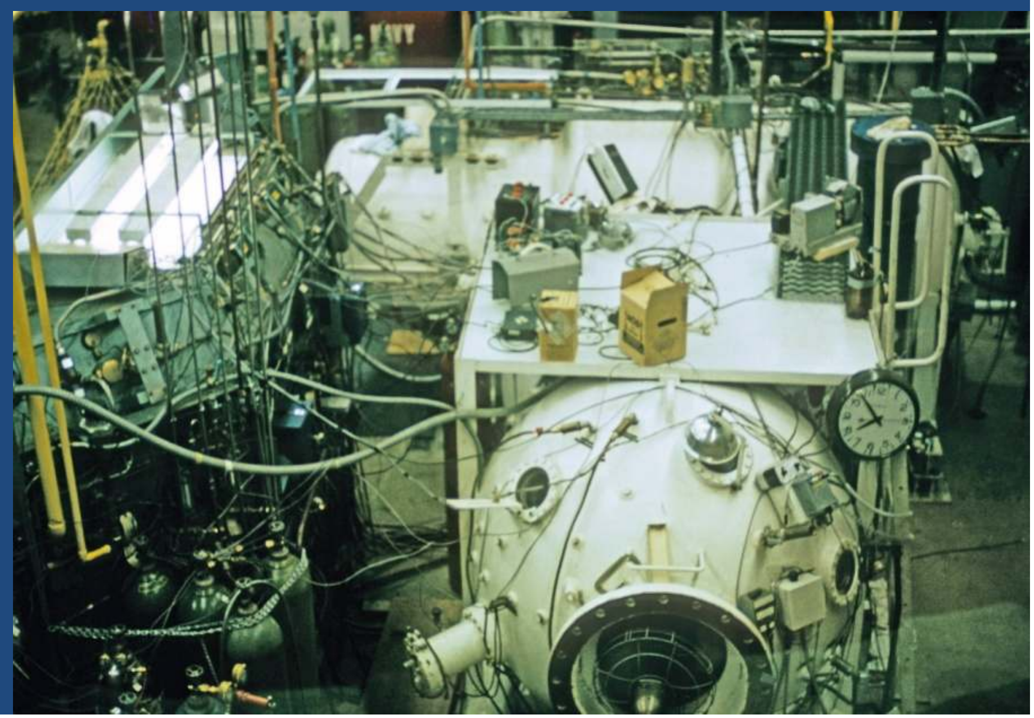
“Deep Underground Tunneling: A New Challenge in Manned Hyperbaric Productivity”

Dave Kenyon
Principal Engineer
Hamilton Research, Ltd.

Lambertsen Lecture

UHMS Symposium
13 June 2013
Orlando, FL



Thanks!

To the following contributors:

Glenn Butler - Life Support Technologies

Mark Chipps – Life Support Technologies

Bernie Chowdhury – Life Support Technologies

Bernie Campoli - for Photos/conversions

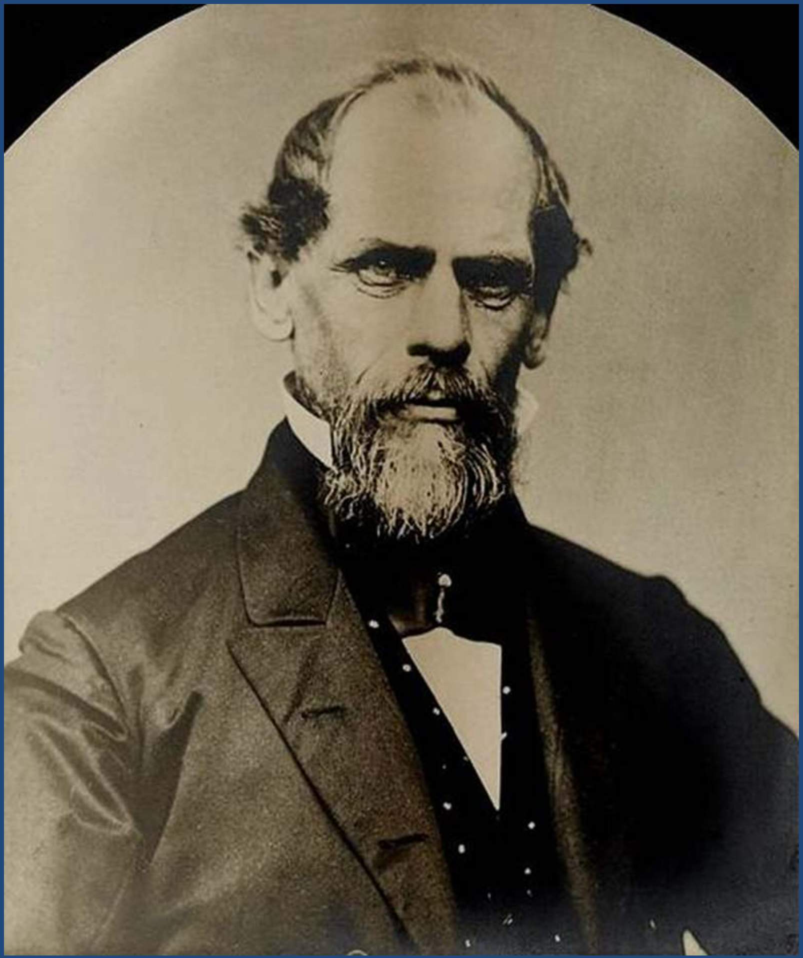
Lecture Agenda

- Background and History
- Challenges
- Early Laboratory Experience
- Extending existing Air/O2 tables to 72 psi
- OEA (Oxygen Enhanced Air)
- Trimix decompression tables using OEA during decompression
- Surface decompression techniques
- Repex techniques and nitrox saturation
- Crude neon – constant PO2 decompression

The Brooklyn Bridge

Construction started: January 3, 1870; completed 1883

John Augustus Roebling



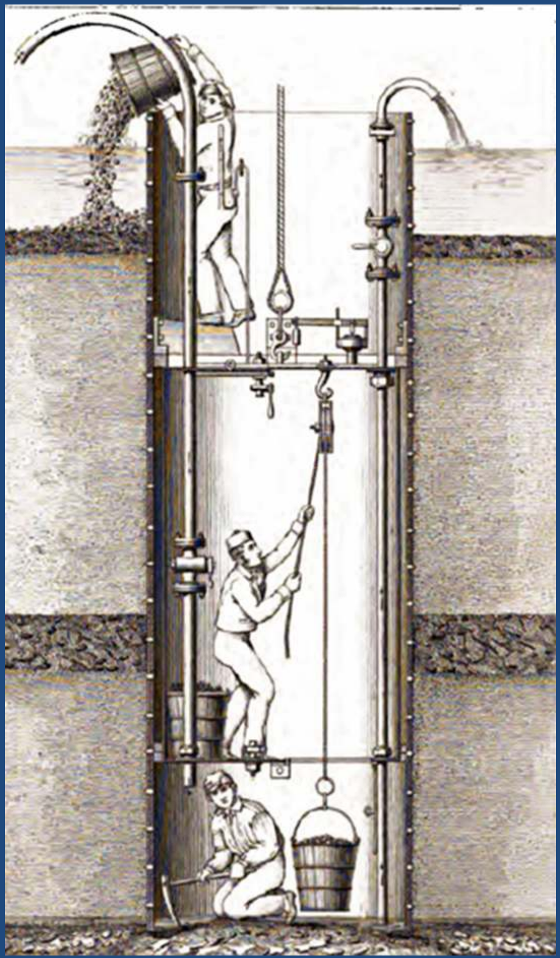
1806 - 1869

Washington Augustus Roebling

- John A. Roebling’s Son; carried on his father work supervising the construction of the Brooklyn Bridge.
- Was debilitated after repeated “Decompression Sickness” events commonly called “Caisson’s Disease”.
- Washington’s wife, Emily Warren Roebling carried on his work while disabled.

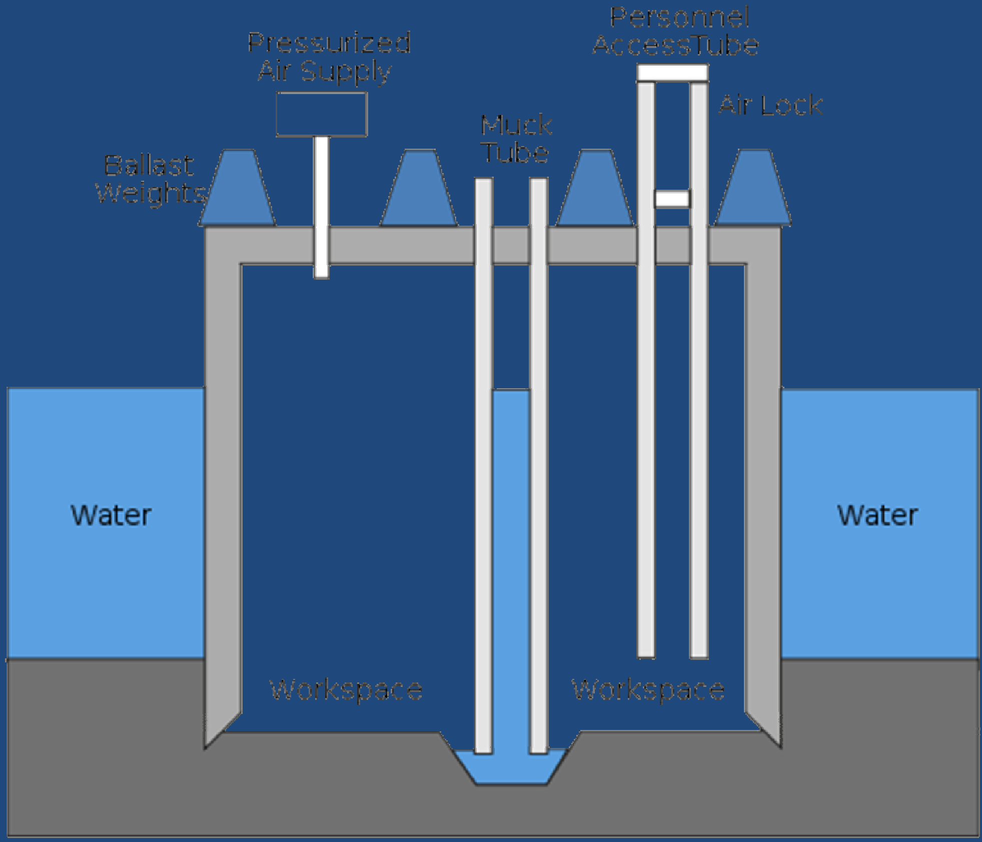
1837 - 1926

Early “Open” Caisson Construction

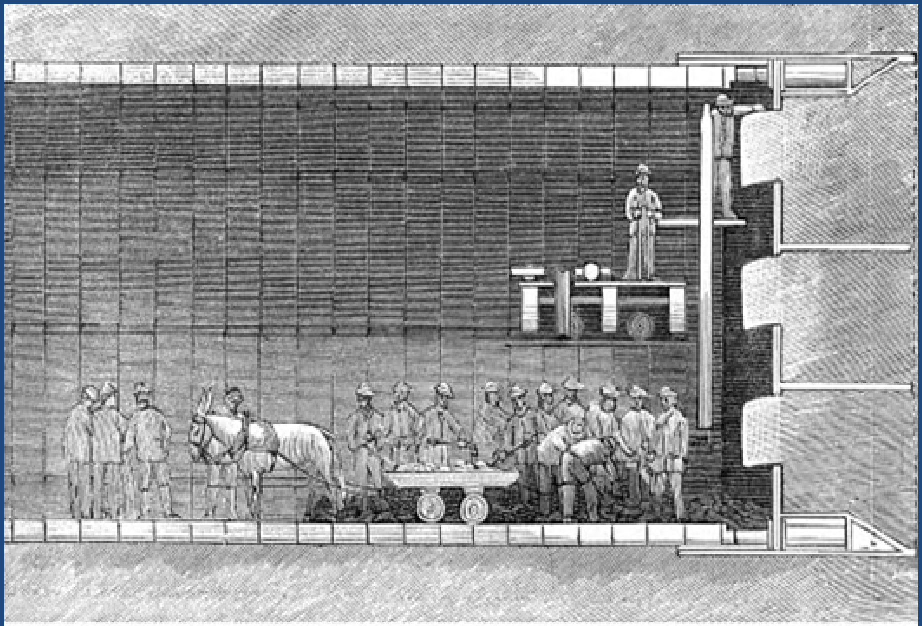


Jules Triger, dated 1846

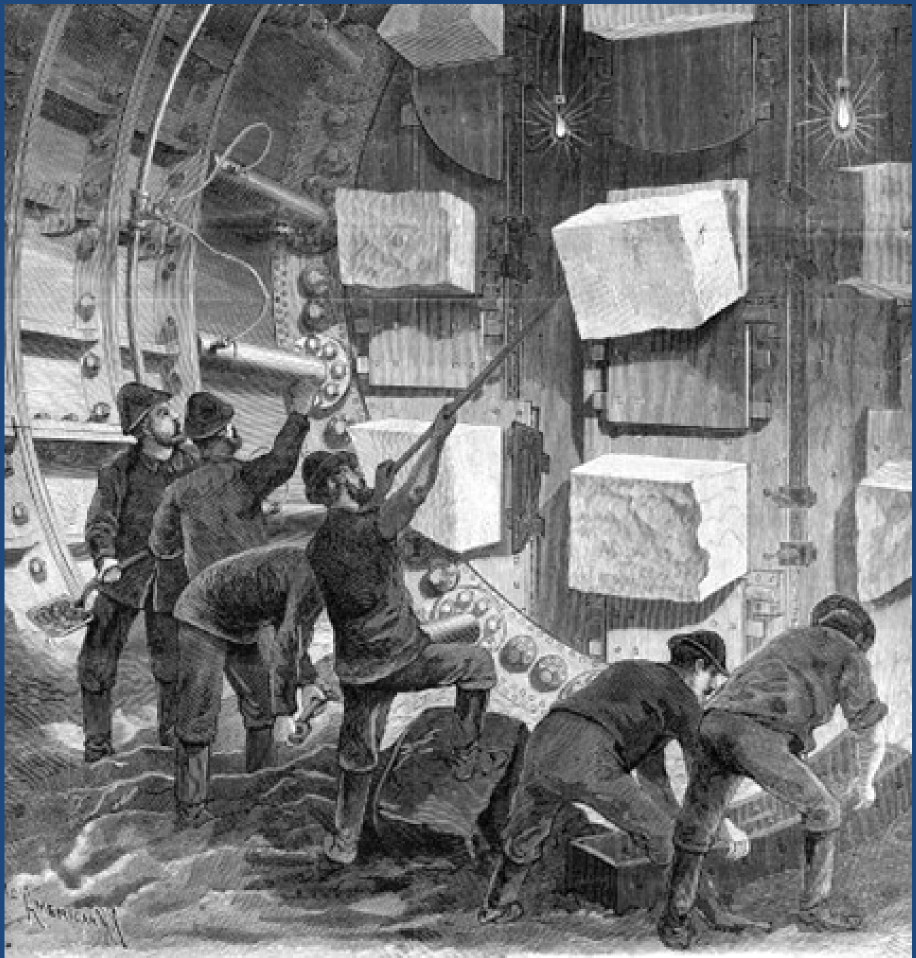
Caisson Schematic – "Pneumatic"



Early tunneling through “Muck”

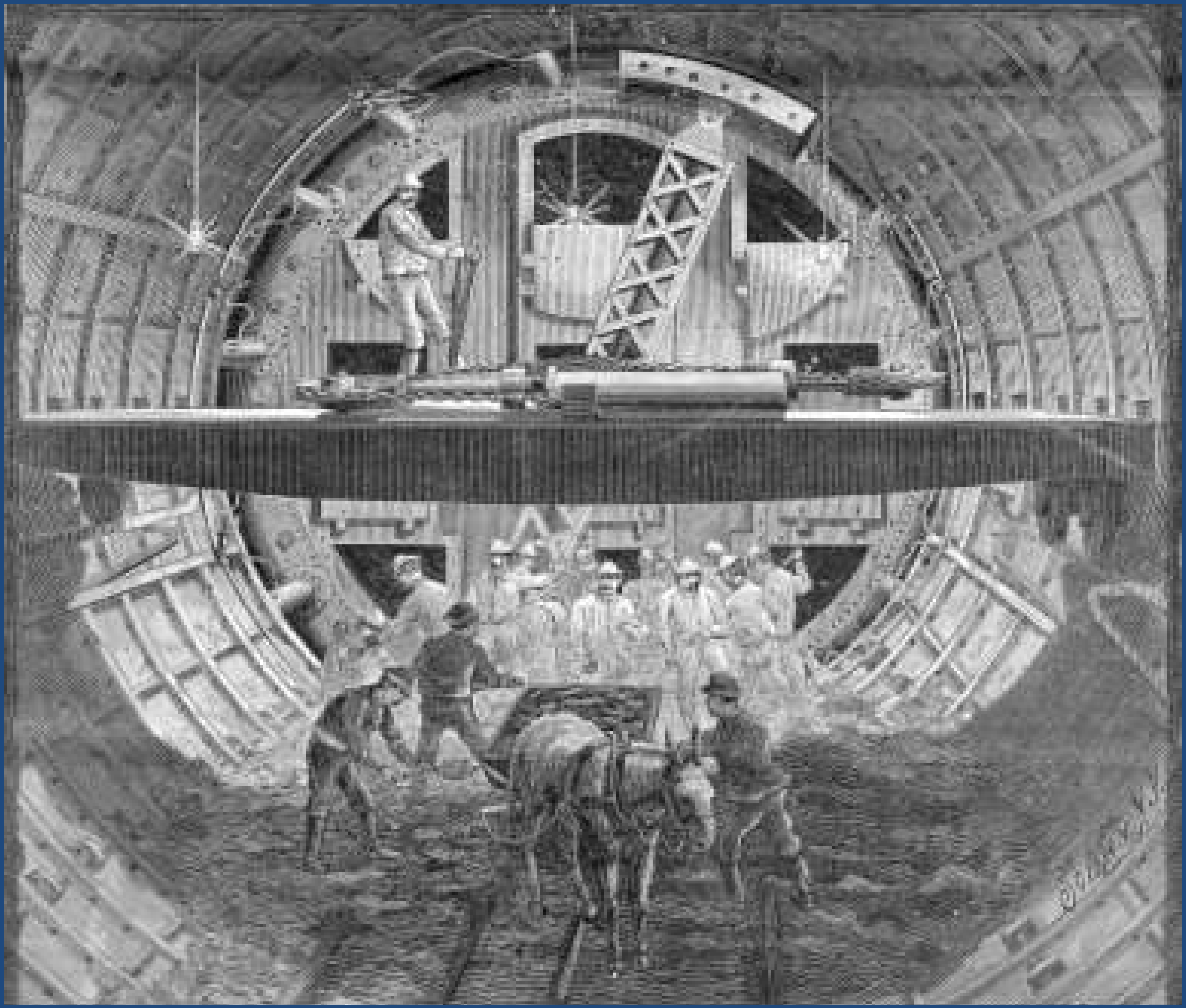


View Showing the Front or Cutting Edges of the Shield

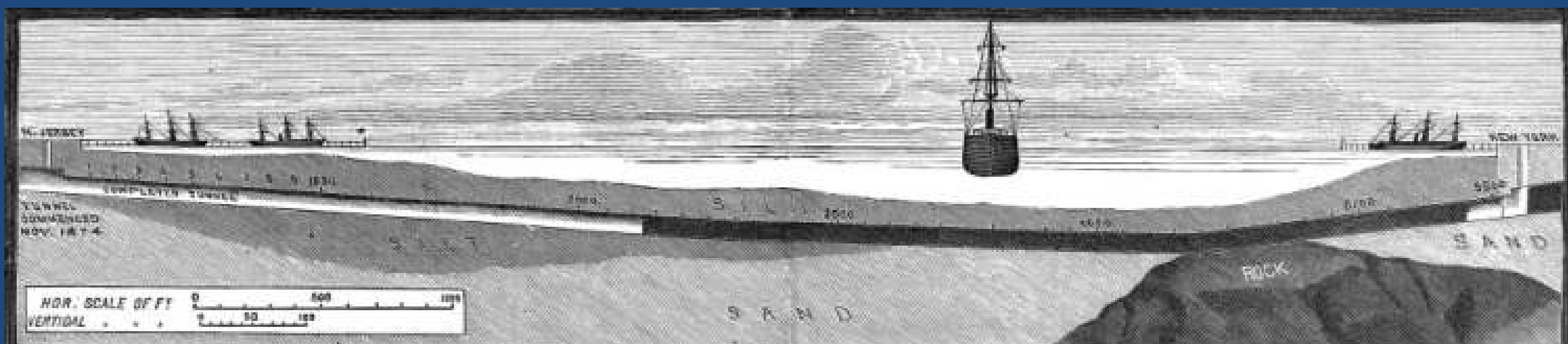


Interior View of Hydraulic Shield and Tunnel

Tunneling is a continuous horizontal Caisson



The Hudson River tunnel; the “Erector” and the hydraulic Shield



THE HUDSON RIVER TUNNEL.

The heavy dark line shows the uncompleted portion.

Decompressing in a Lincoln Tunnel Chamber circa 1934

Under the East River, NYC

Early Tunneling

- Was muddy, dirty and cold
- Hard work, requiring strong men
- Dangerous, and often loss of life
- In the NY City area, a strong Union
  - Sand Hog Union; Local 147
  - Intervention times <240 min for compressed air work

Tunneling has come a long way

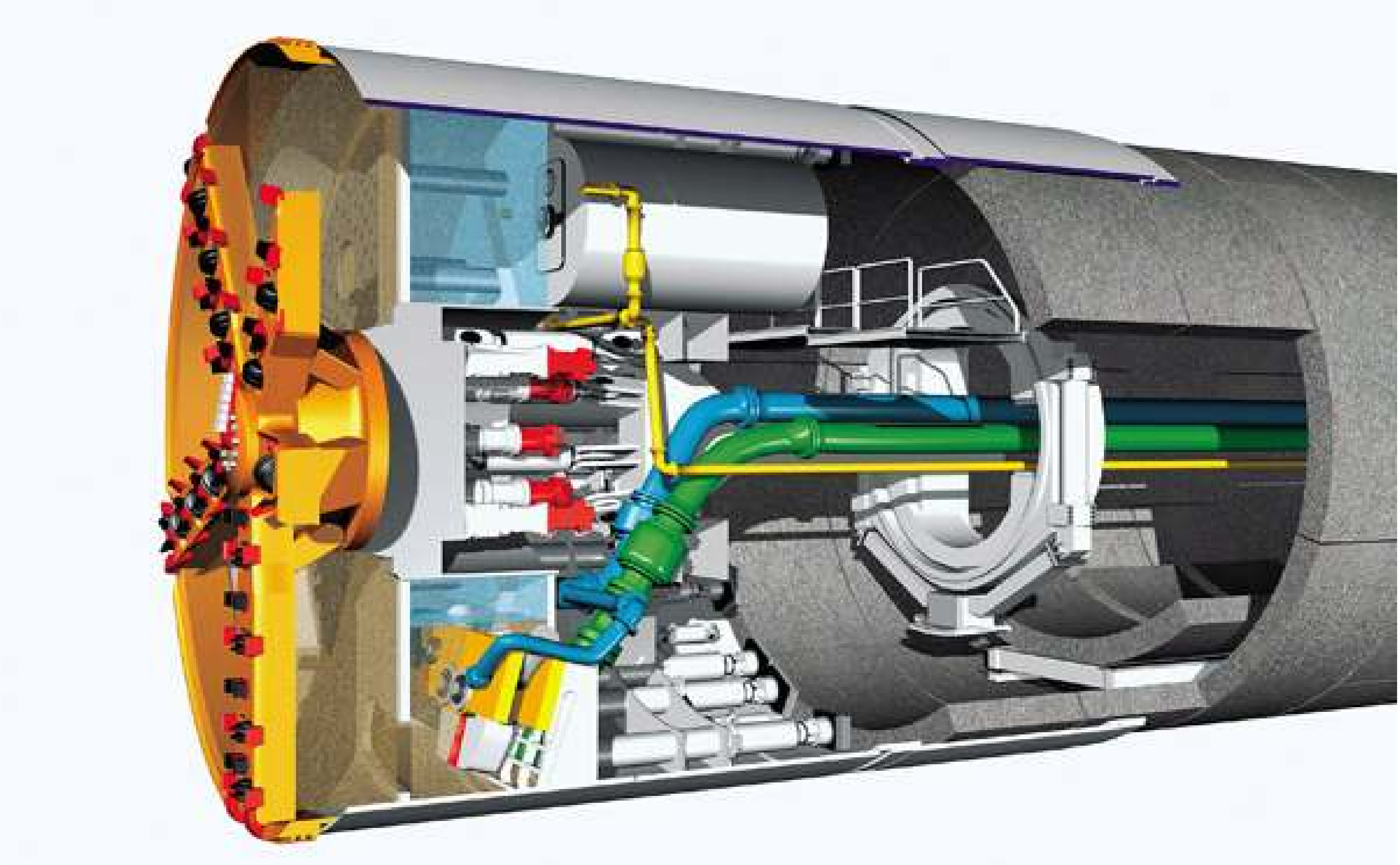
Cutter Heads

Tunnel Boring Machine (TBM) Used for the MTA's "East Side Access Project"

Yucca Mountain TBM

Gotthard Base Tunnel

Why the need for a HBO chamber in a TBM?



Challenges

- Tunneling Projects need to go deeper!
- Air is limited to pressures < approx. 75 psi (150 fsw or 50 msw or 5 bar).
- Mix Gases when going deeper than 75 psi.
- Special breathing equipment needed.
- Possible portable recompression chambers needed for advanced pressure projects.
- Training, training and more training!

Deep Tunneling Project will use technologies from other industries

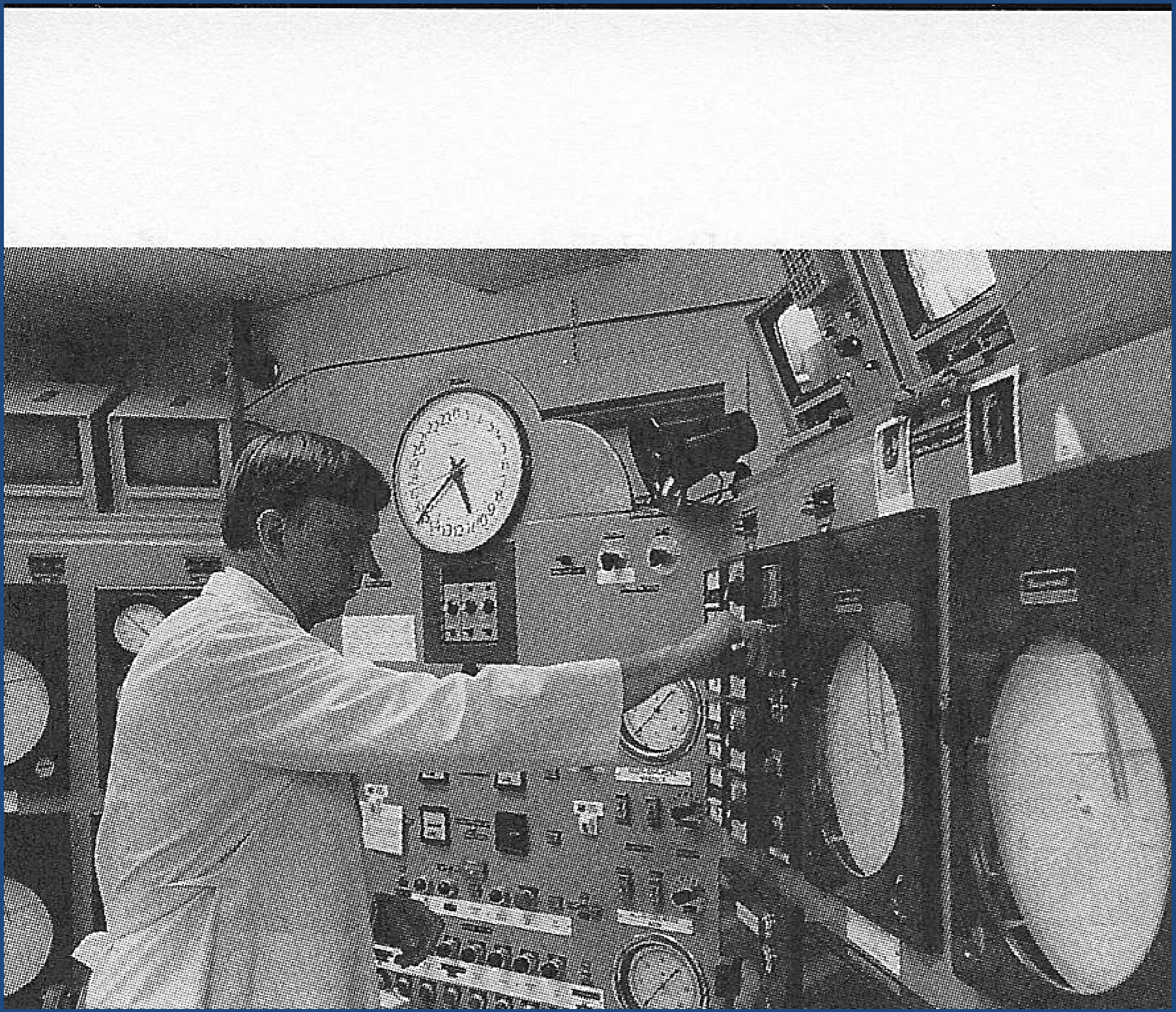
- Military Diving
- Technical Diving
- Commercial Deep Diving - Mixed Gas systems
- Saturation Diving
- Aerospace

Dr. Chris Lambertsen

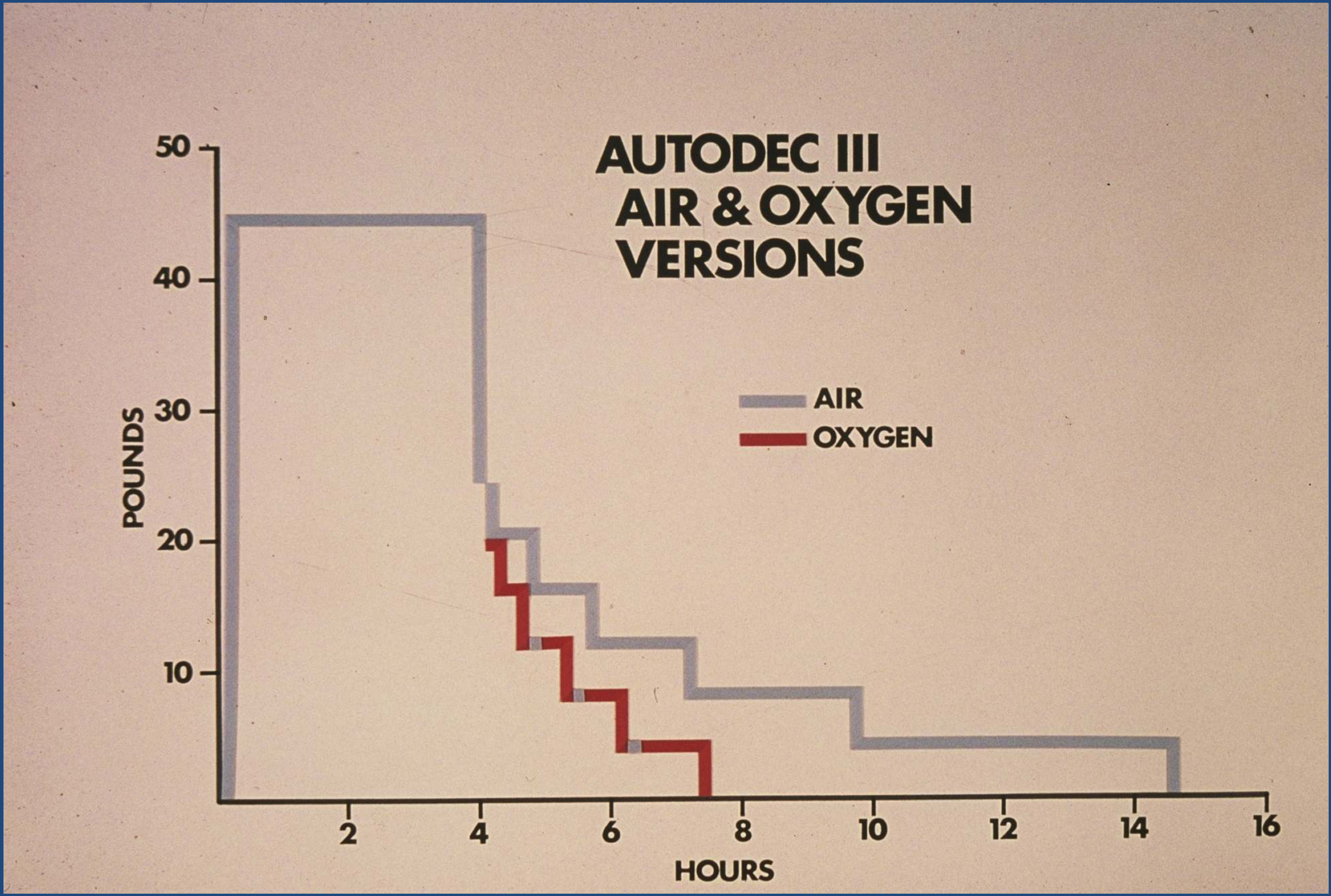
"the father
of the
Frogmen"

1917 - 2011


Dr. Eric P. Kindwall
"The Teacher"
KINDWALL

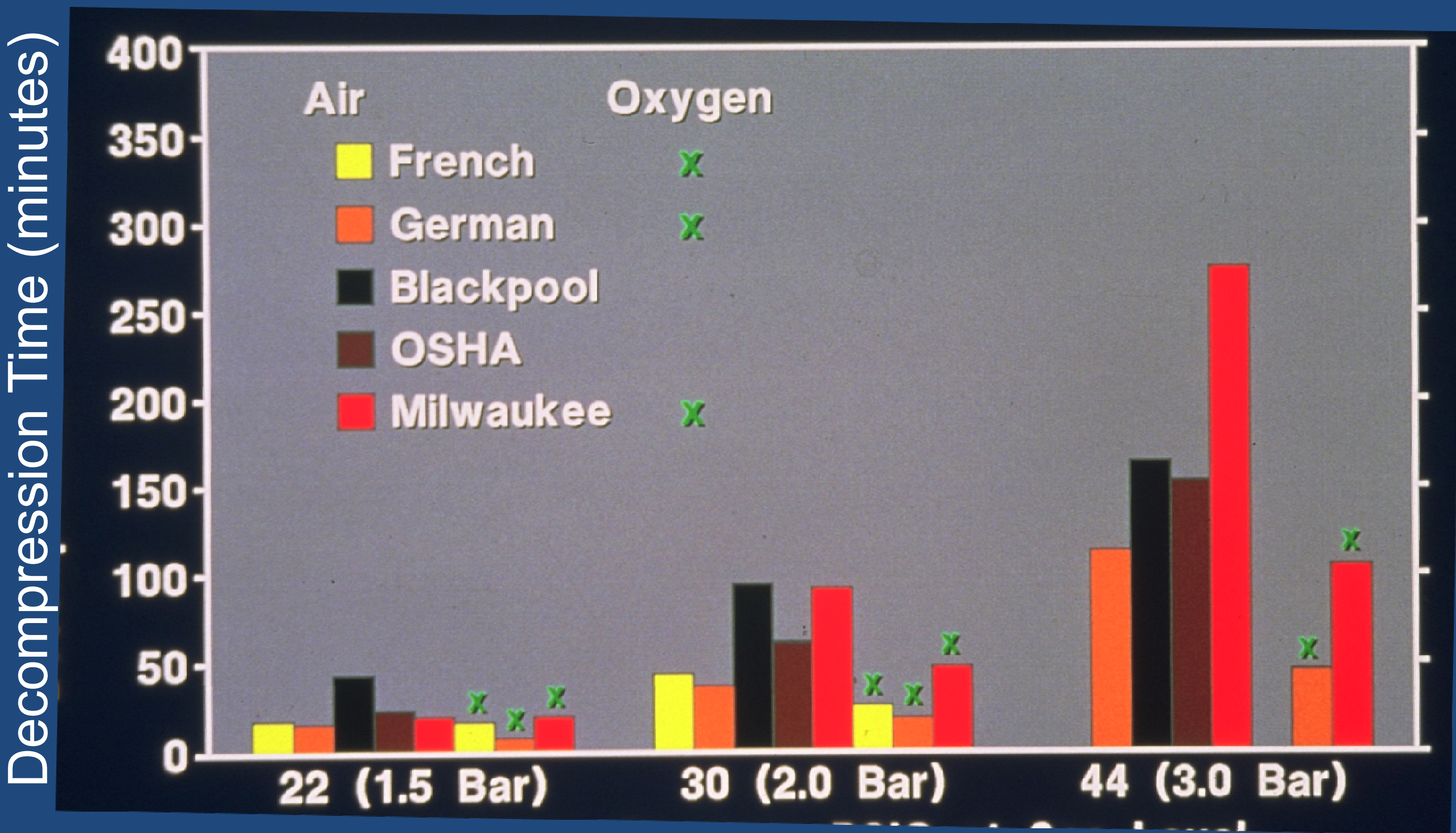


Dr. Eric Kindwall working on the Autodec III decompression tables

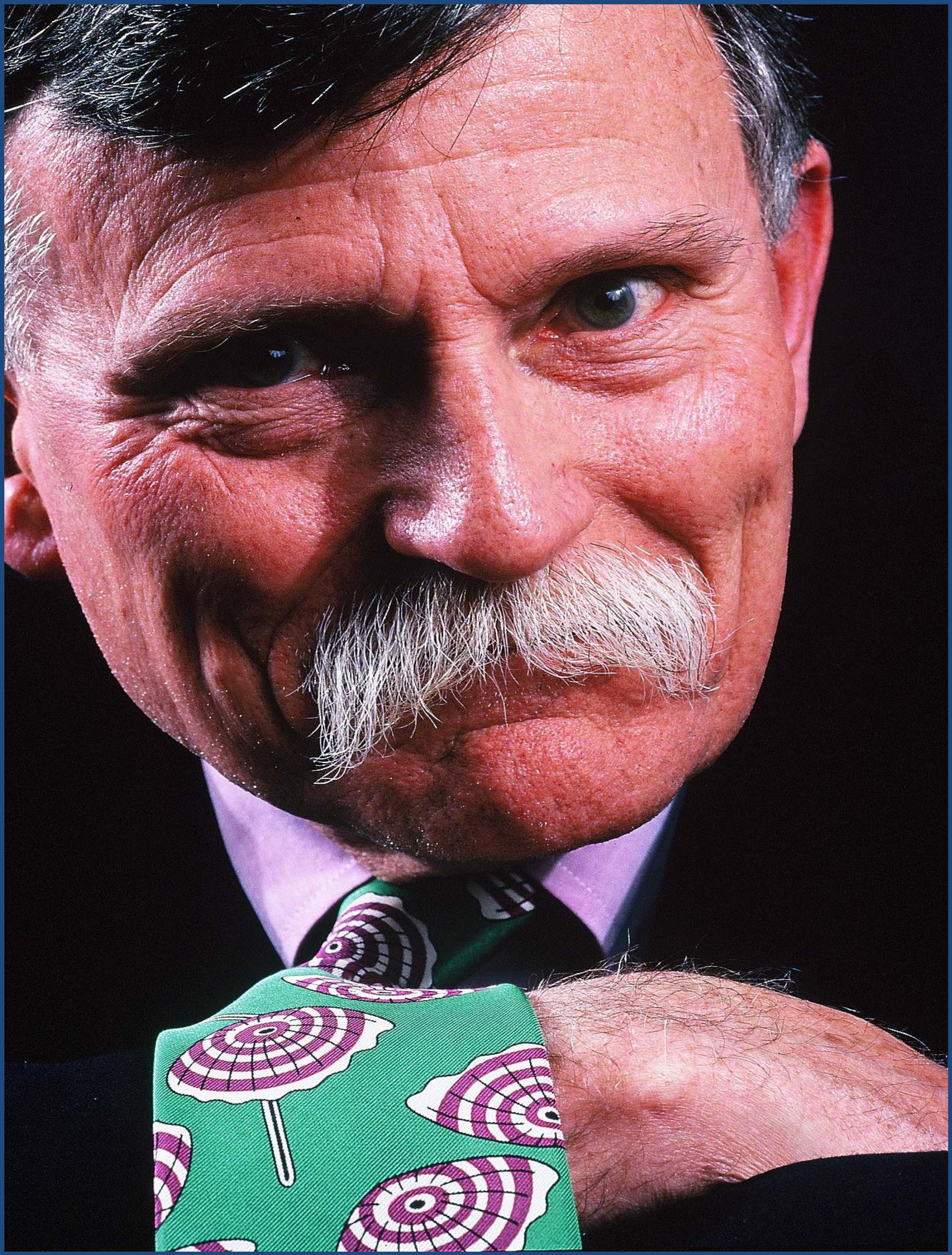


AUTODEC III
AIR & OXYGEN
VERSIONS
AIR
OXYGEN
POUNDS
50
40
30
20
10
2
4
6
8
10
12
14
16
HOURS

Comparison of decompression times for 2 hours of Compressed Air work



Exposure Pressure PSIG at Sea Level



R. W. Hamilton, PhD

1930 - 2011

“Billy Bob”

A great scientist and a true friend

The “Father” of Technical Diving

R.W. Hamilton at work circa 1950

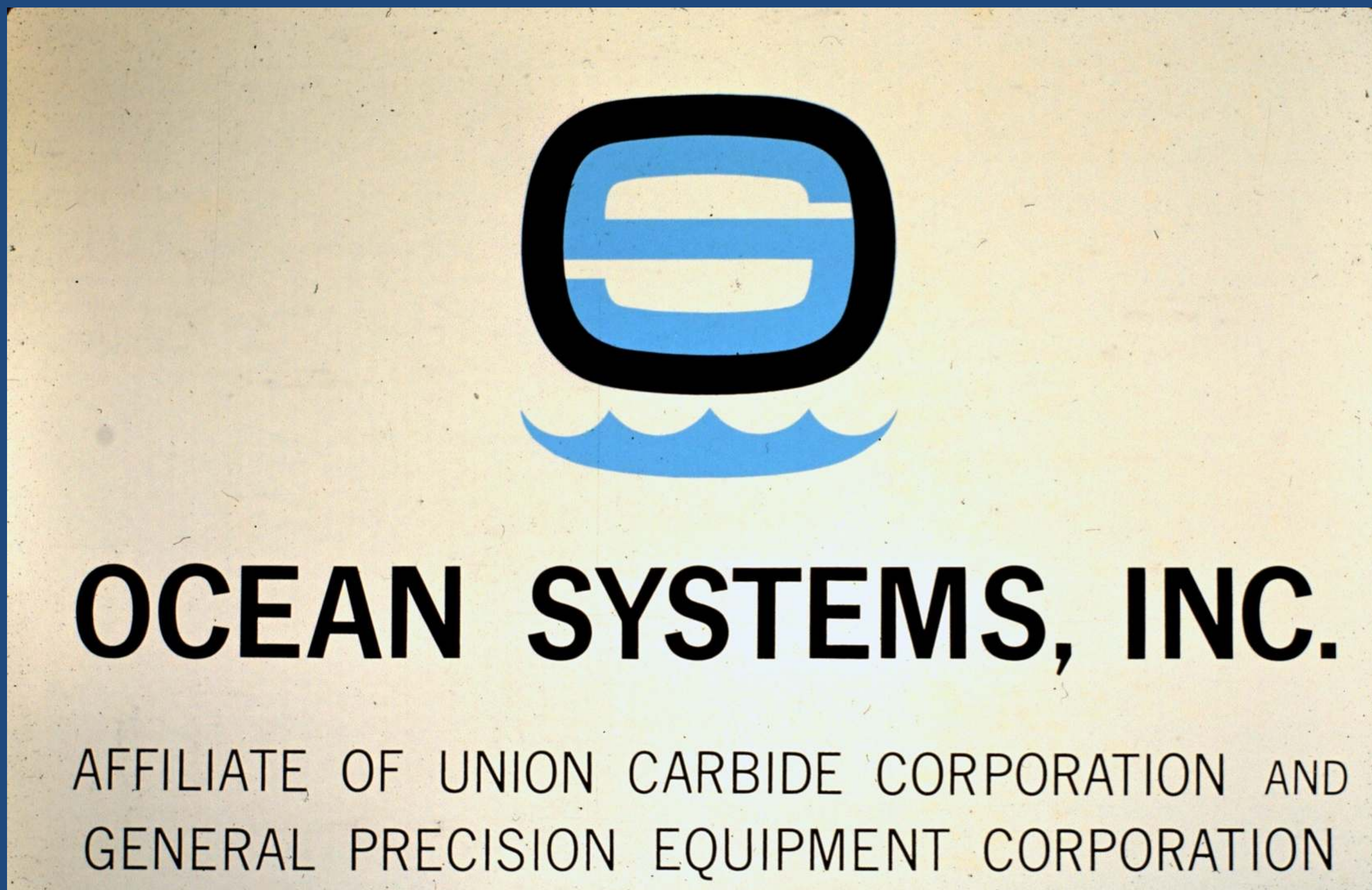
R.W. Hamilton at work circa 2011

1950 >>> 62 years >>> 2011

Still eating that same banana !!

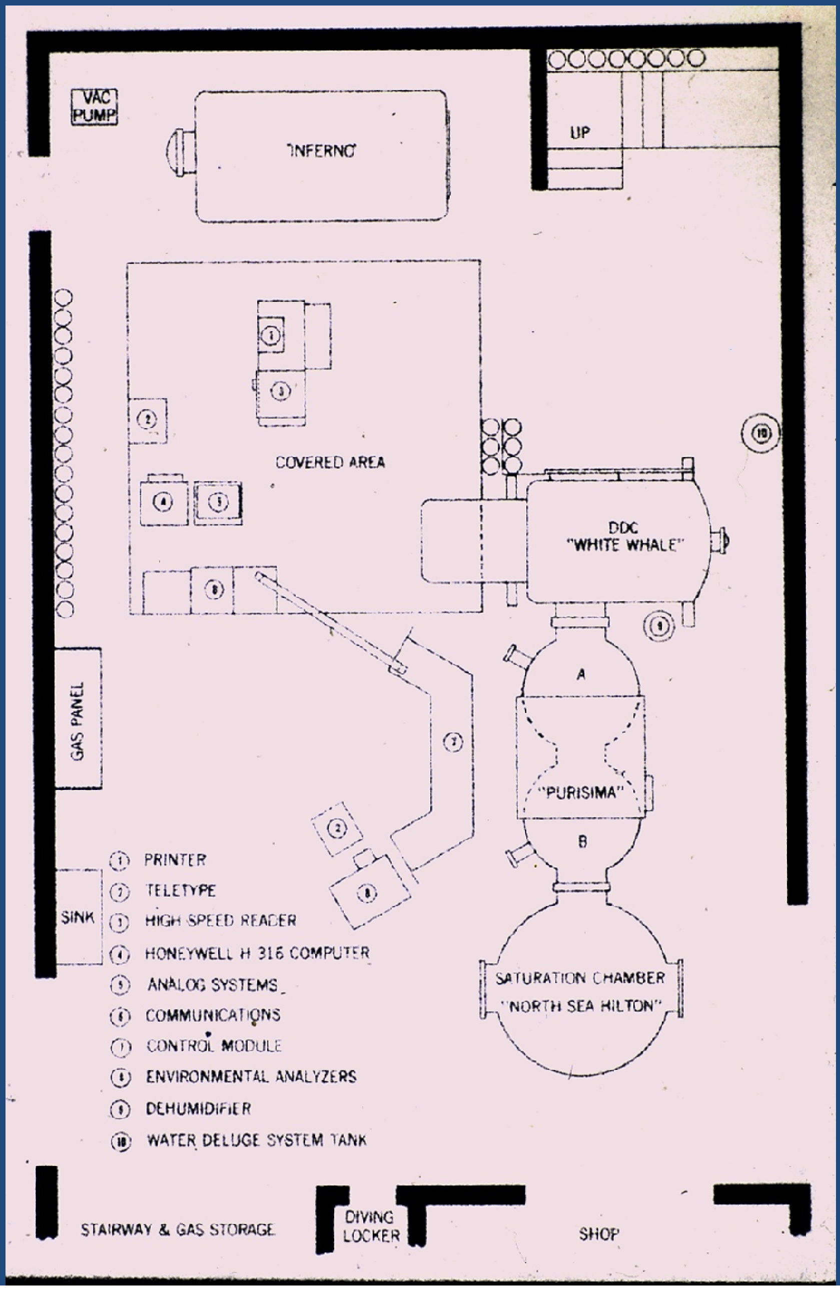
Bill joined the Air Force after receiving his Bachelor's degree '51

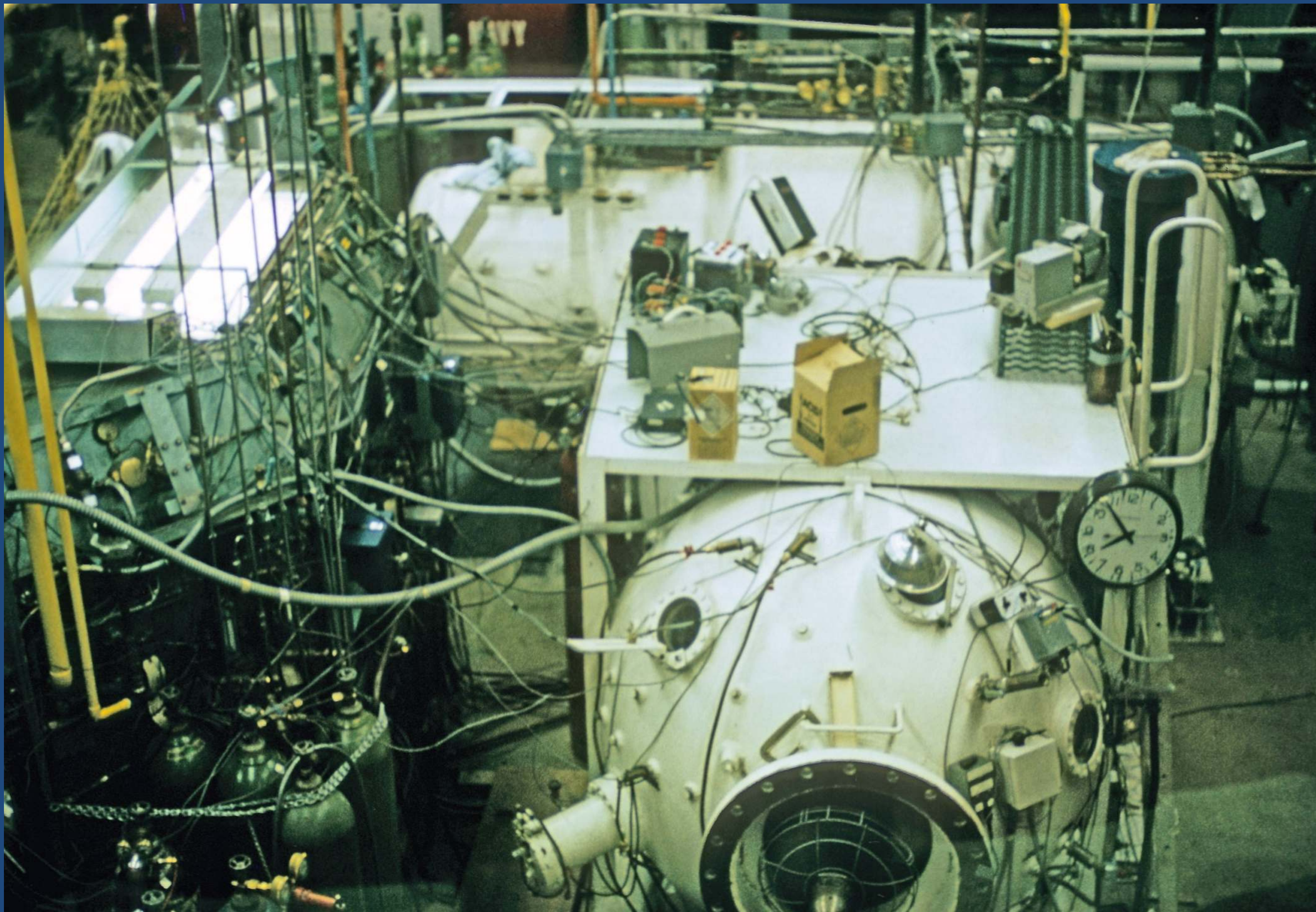
Bill joined Ocean Systems Inc. in 1964



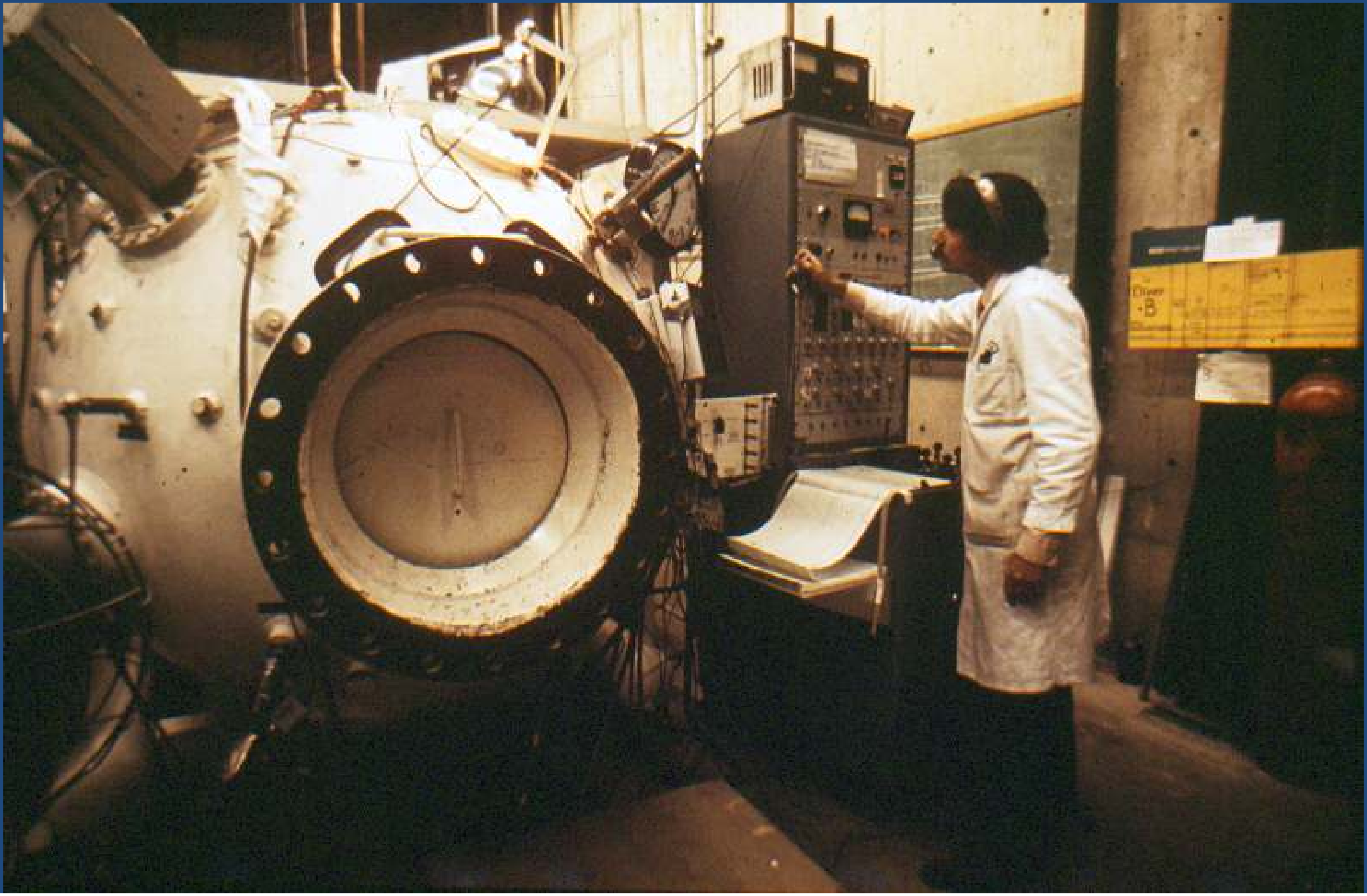
Called back into service for the Viet Nam War in 1968 with the Air Force Reserves

Bill returned in 1970 just in time to rebuild the lab now moved to Tarrytown, NY.

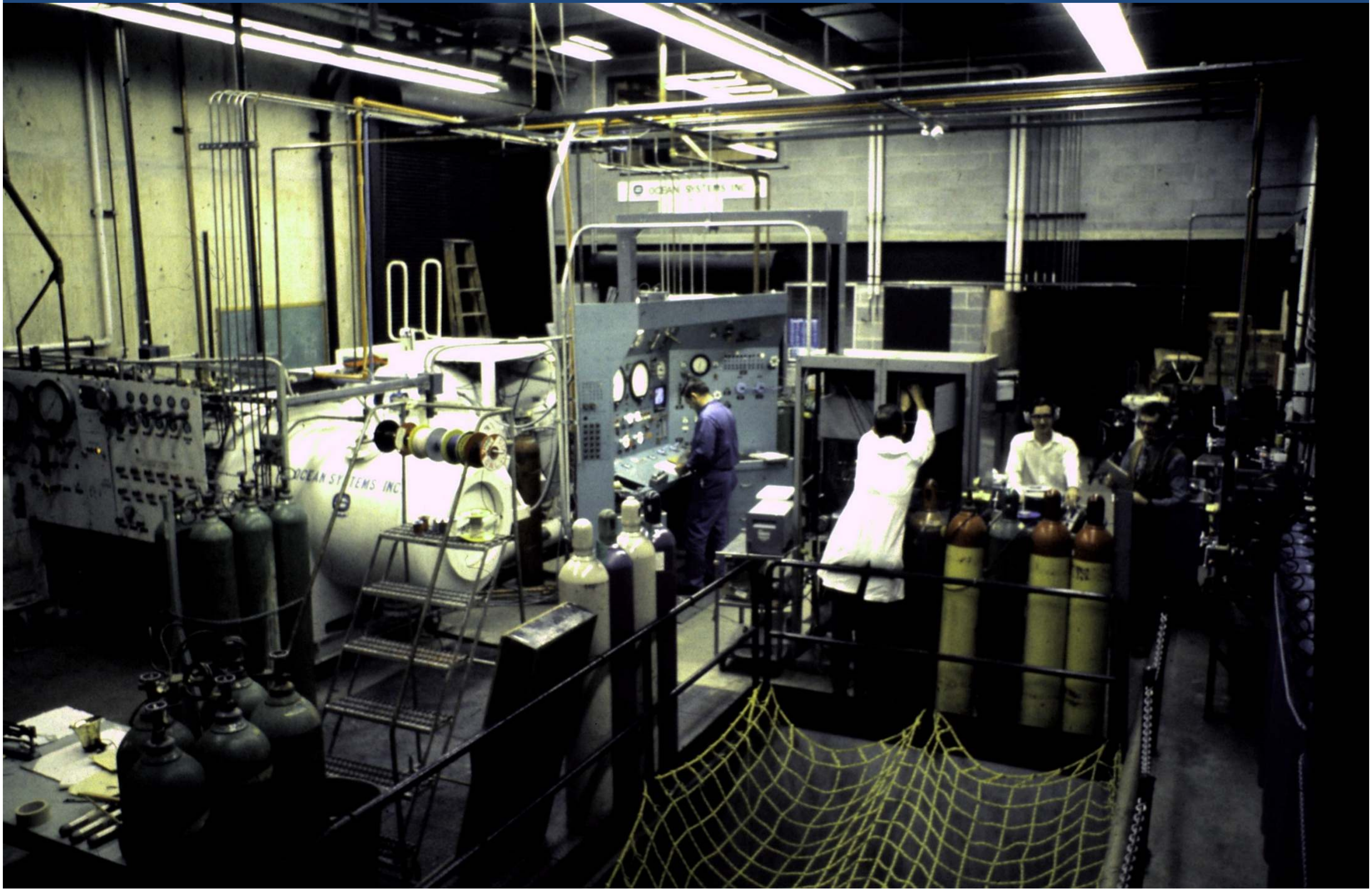




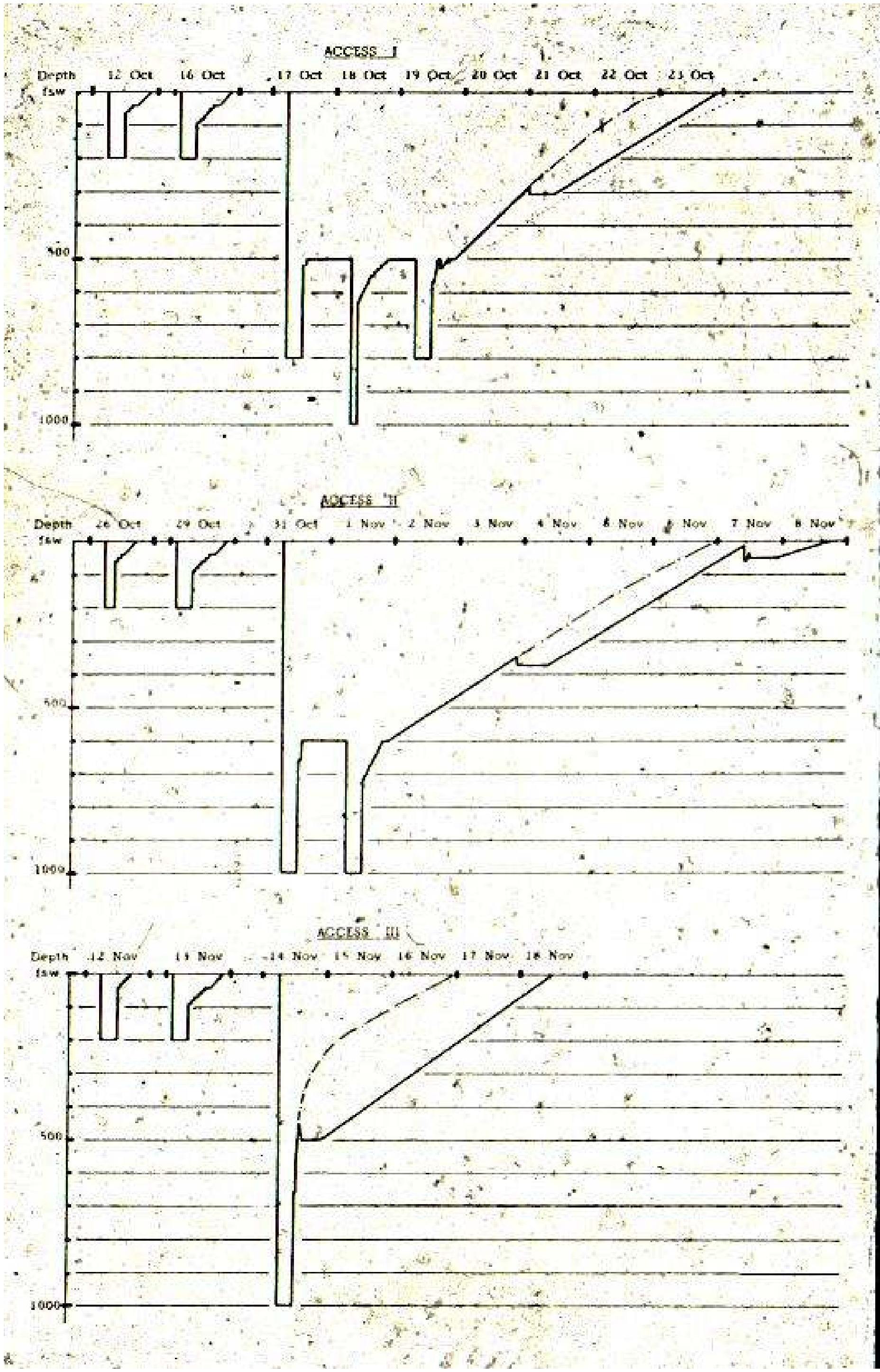
Bill Hamilton taking Data



Back view showing Purisima Mated to the old "OSI ADS" DDC "White Whale"



Tank “farm” outside the lab at Tarrytown, NY

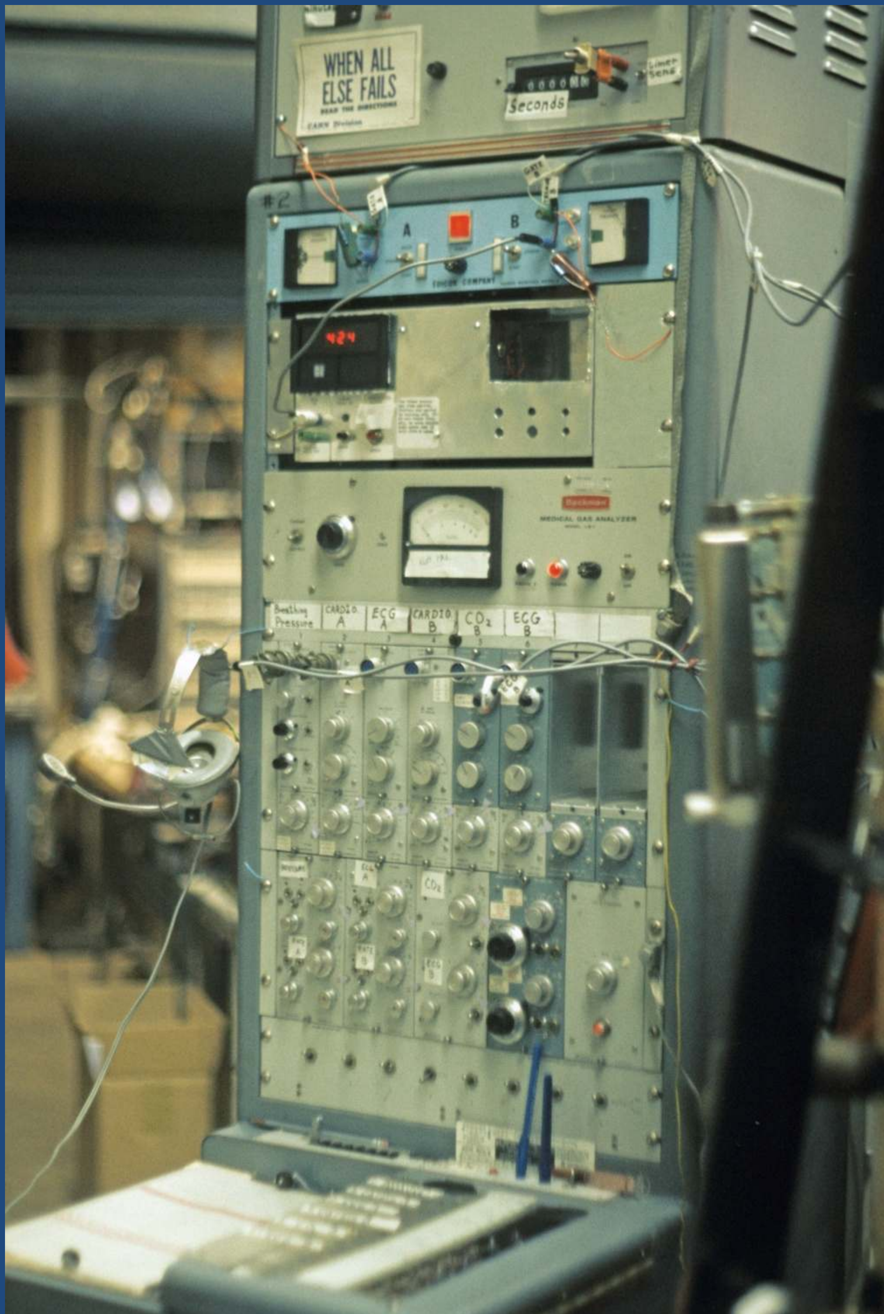


Access project

- Saturation at 500 and 600 fsw
- Excursions to 1000 fsw
- Minimal Decompression back to the habitat

Purisima's Control center

Communications Control



Physiology Data Acquisition

Bill taking notes on a

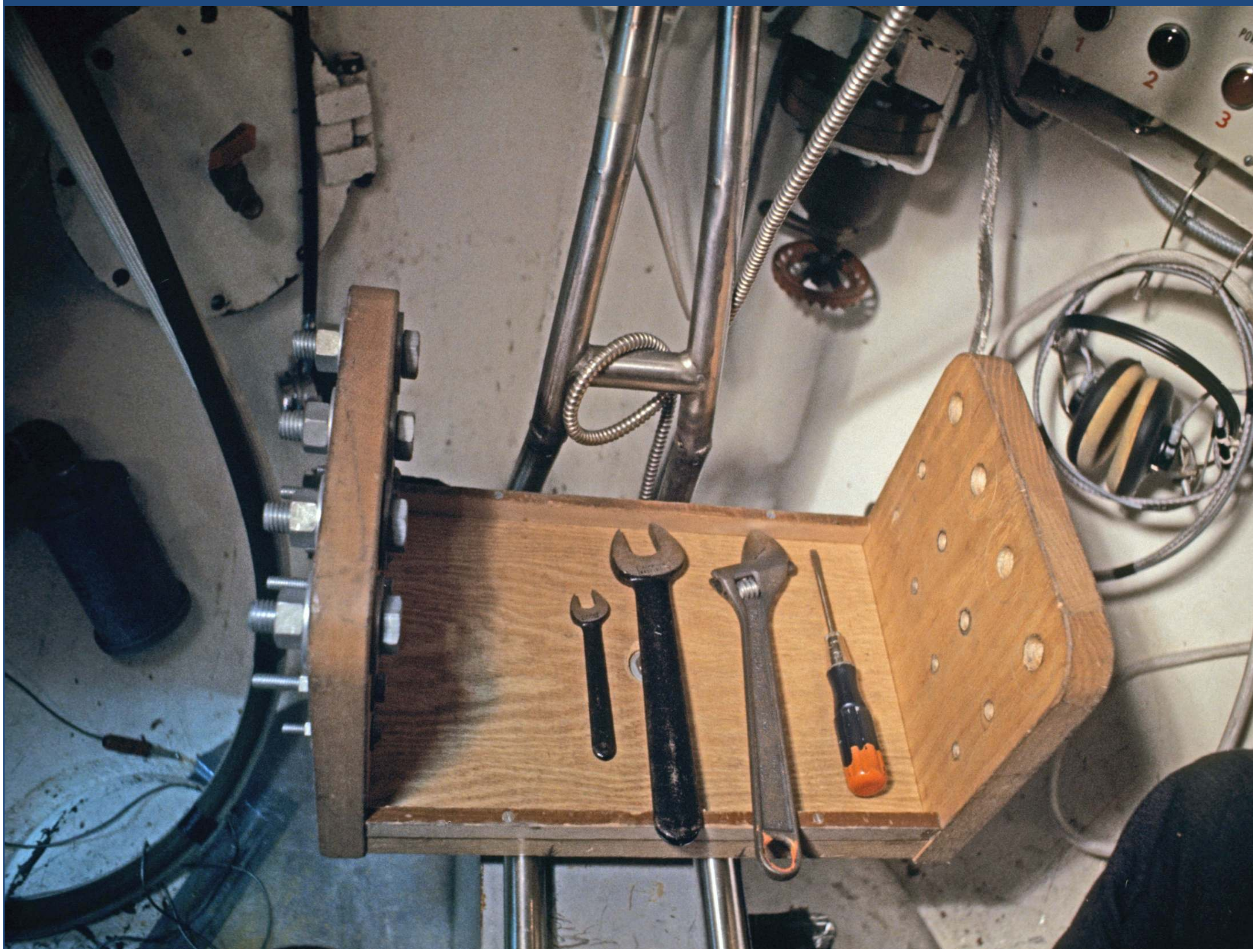
Deep Dive

In one sphere a diver would do an ergometer test.

In the other sphere a diver perform a mechanical dexterity test; moving nuts and bolts from one side to another.

CO2
Scrubber

Manual Dexterity Test



. . . why would a diver / student

Sign-up as an experimental diver at $5/hour . . .

????


OCEAN SYSTEMS INC.
100
Fathom
Club
EXPERIMENTAL DIVER

Purisima as a Research Tool 1969 to 1977

- < 1969 - Ocean Systems ADS I
- 1969 to 1970 - Linde Division, Tonawanda, NY
- 1970 to 1974 - Union Carbide Research Institute, Tarrytown, NY
- 1974 to 1979 - Tarrytown Labs, Tarrytown, NY
- 1979 to 1986- IUC (gas storage vessel)
- 1992 - Transferred to the Wilson family Estate
- 2011 to now – SB Maritime Museum

Purisima
at the
Santa Barbara
Maritime
Museum
2012

Purisima as a Research Tool

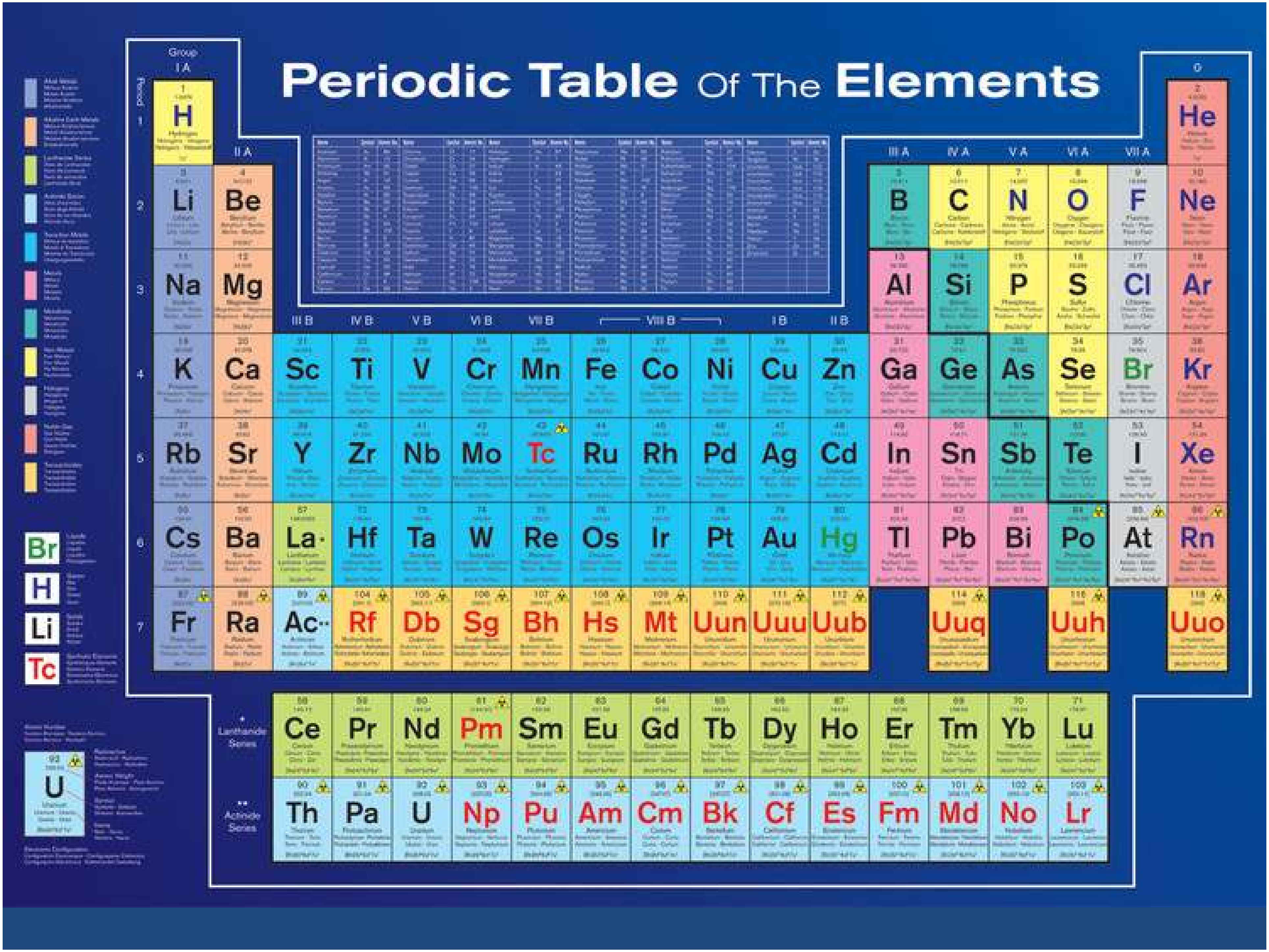
- Development of very deep "Bounce" Bell diving decompression tables up to 1000 fsw
  - OSI Mk VI, Mk VIII and Mark IX (Crude Neon)
- NOAA OPS excursion Tables for Shallow Saturated No-Stop Excursion Decompression Tables
- Saturation Decompression Tables (Air, He and Crude Ne)
- **ACCESS**: very deep excursions from deep habitats
  - Diver training
  - Equipment evaluation
  - NASA, BuMed, ONR, Air Force special decompression studies (manned and animal)

Neon Performance Series

Why Neon?

Interesting Facts about Neon

- 0.0018 percent of Earth's atmosphere is neon.
- Although it is relatively rare on our planet, neon is the forth most abundant element in the universe behind H2, He and O2.
- If you could gather all the neon from the rooms in a typical new home, you would get 10 liters (2 gallons) of neon gas.
- Neon forms in stars with a mass of eight or more Earth suns.
- Neon has no stable compounds.

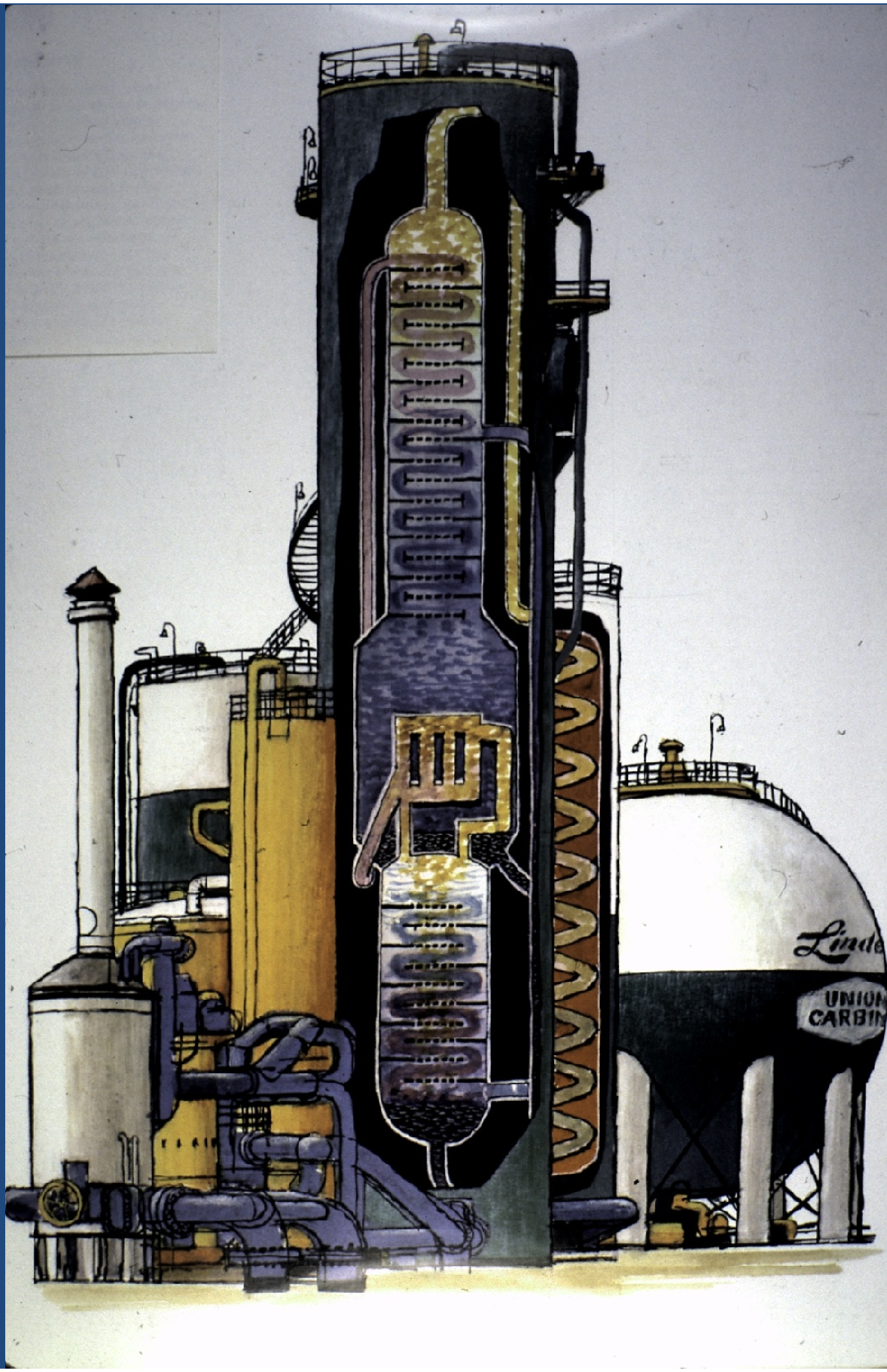

Periodic Table Of The Elements
Group
I A
Period
II A
III B IV B V B VI B VII B VIII B I B II B
III A IV A V A VI A VII A
0
1 H He
2 Li Be B C N O F Ne
3 Na Mg Al Si P S Cl Ar
4 K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr
5 Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe
6 Cs Ba La· Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn
7 Fr Ra Ac·· Rf Db Sg Bh Hs Mt Uun Uuu Uub Uuq Uuh Uuo
· Lanthanide Series
Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
·· Actinide Series
Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No Lr
Br
H
Li
Tc
U

Neon Properties

- Classification: Neon is a noble gas; non-metal
- Color: colorless
- Atomic weight: 20.180
- State: gas
- Melting point: -248.57 ^{o}C, 24.53 K
- Boiling point: -246.0 ^{o}C, 27.1 K
- Electrons: 10 Protons: 10 Neutrons 10
  Electron shells: 2,8
- Density @ 20^{o}C: 0.0009 g/cm^3

Cost of Pure Neon – not practical

- Pure Neon is over 32 times the cost of Helium
- Helium can be found in abundance together with Natural Gas as a by-product of radioactive decay; **Neon can only be extracted from the air.**
- Each breath of Pure Neon-Oxygen Mixture at 400 fsw (13.1 Atm) is approximately $20
- Crude Neon is an alternative


Linde
UNION
CARBI

Crude Neon
Patent # 5,100,446
Union Carbide Mar 1992

- A crude neon production system wherein a small neon-containing stream is taken from a cryogenic air separation plant and processed in a neon column and in a non-cryogenic pressure swing adsorption system to produce crude neon and wherein tail gas from the pressure swing adsorption is recycled back into the air separation plant.

Crude Neon Advantages

- Costs could be lower than Helium if the patented process was employed at a large commercial scale.
- Warmer for divers immersed in the lock-out gas.
- Speech is more intelligible . . . .
  (a "mature" Donald Duck)
- Available world wide at liquefaction plants

Crude Neon

- Neon 50
  - 50 to 60% Ne, 20 t0 30% N2, Balance He
- Neon 75
  - 70 to 80% Ne, Balance Helium

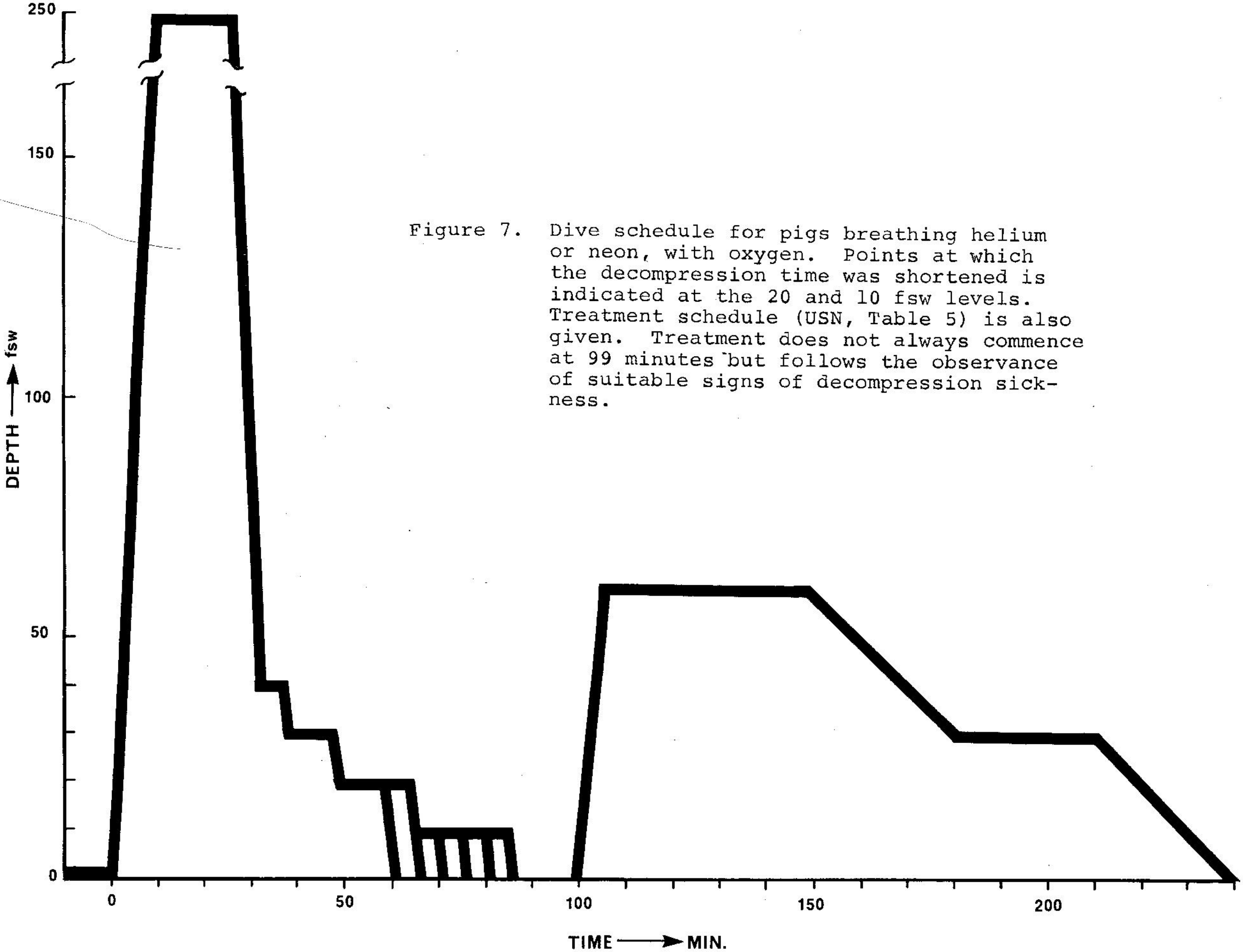


Figure 7. Dive schedule for pigs breathing helium or neon, with oxygen. Points at which the decompression time was shortened is indicated at the 20 and 10 fsw levels. Treatment schedule (USN, Table 5) is also given. Treatment does not always commence at 99 minutes but follows the observance of suitable signs of decompression sickness.

Summary of pig Decompressions: Severity Score and Time to Recompression

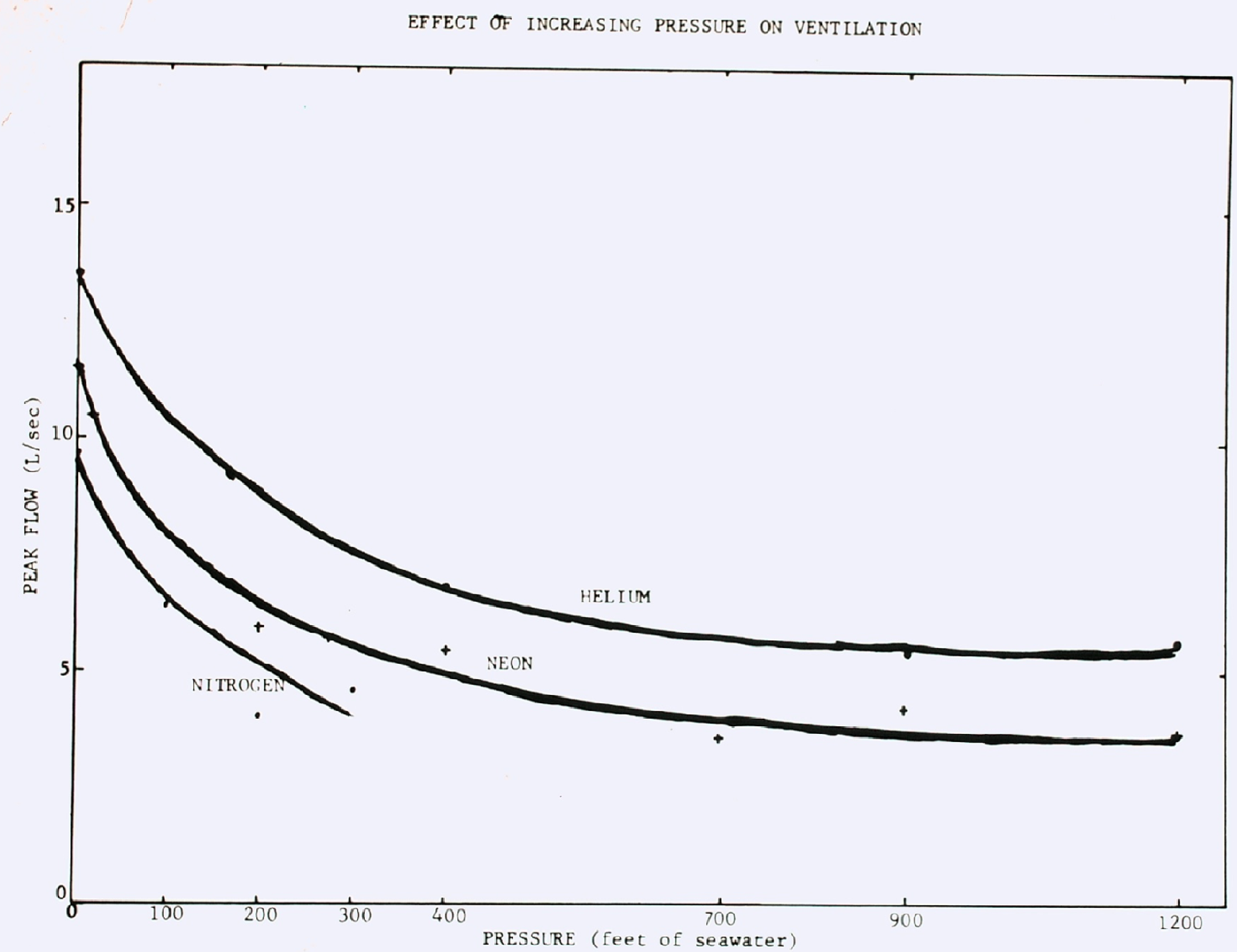
Subject's Name	Gas	Decompression to sea level was begun after: 10 min at 20 fsw	15 min at 20 fsw	5 min at 10 fsw	10 min at 10 fsw	15 min at 10 fsw	20 min at 10 fsw
1. CASPER	HeO_2			4/9	3/14	1/60	1/60
	NeO_2			4/16	3/11	1/60	
	NeN_2HeO_2				4/12		
2. HUFF & PUFF	HeO_2		5/18	3/34	2/42	2/21 2/60	
	NeO_2		3/21	4/16		1/60	
	NeN_2HeO_2				3/30		
3. NAPOLEON	HeO_2		4/5	3/5	4/5	3/30	2/60
	NeO_2				4/9	3/15	
	NeN_2HeO_2				3/18		
4. LUCY	HeO_2	3/10.5	1/60 2/60				
	NeO_2	3/11	1/60				
	NeN_2HeO_2	4/5					
5. HITLER	NeO_2						1/60

Neon Performance Series

- Manned studies at simulated 300 fsw and 400 fsw on air, but using normoxic O2, actual depth is shallower.
- Evaluate various breathing gases at the bottom:
  - N2 (normoxic)
  - He O2 mix (normoxic)
  - Ne (pure normoxic)
  - Ne 75 (normoxic O2 balance 75% Ne 25% He
  - Nitrous Oxide (laughing Gas)

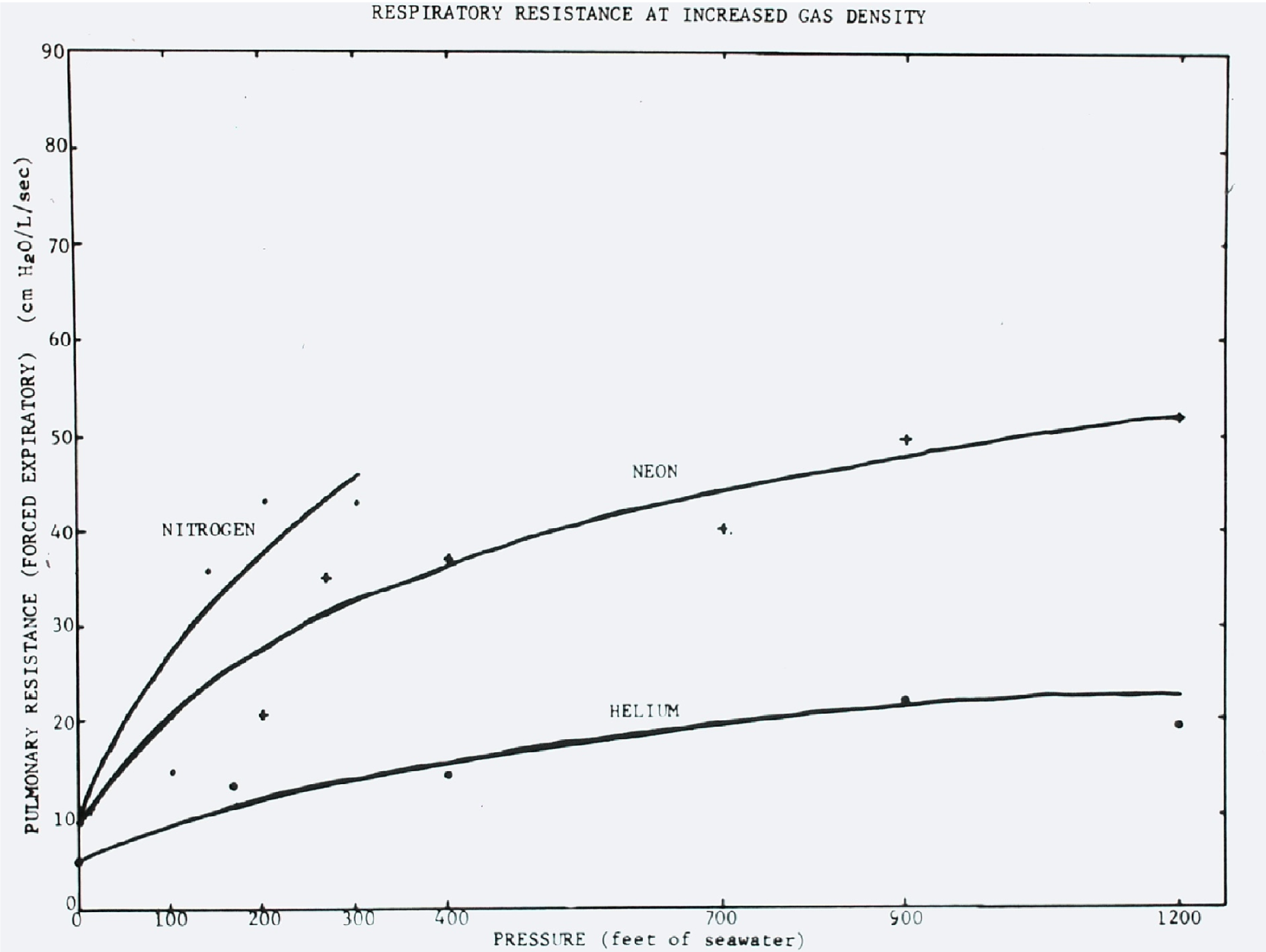
Neon Performance Series

- Manned Dives at 680 fsw on Ne 75 mixtures which was the estimated depth of the open water dives needed off the coast of Africa.
- Manned Dives at deeper depths to look at a practical limit for Neon:
  - Depth of up to 1200 fsw
  - Crude Neon 75
  - Done at the IFEM facility, University of Pennsylvania.



EFFECT OF INCREASING PRESSURE ON VENTILATION
PEAK FLOW (L/sec)
15
10
5
0
0
100
200
300
400
700
900
1200
PRESSURE (feet of seawater)
HELIUM
NEON
NITROGEN


EXPERIMENTAL



RESPIRATORY RESISTANCE AT INCREASED GAS DENSITY
PULMONARY RESISTANCE (FORCED EXPIRATORY) (cm H2O/L/sec)
90
80
70
60
50
40
30
20
10
0
NITROGEN
NEON
HELIUM
0
100
200
300
400
700
900
1200
PRESSURE (feet of seawater)


CODE
UP


EXPERIMENTAL

And now out to sea!

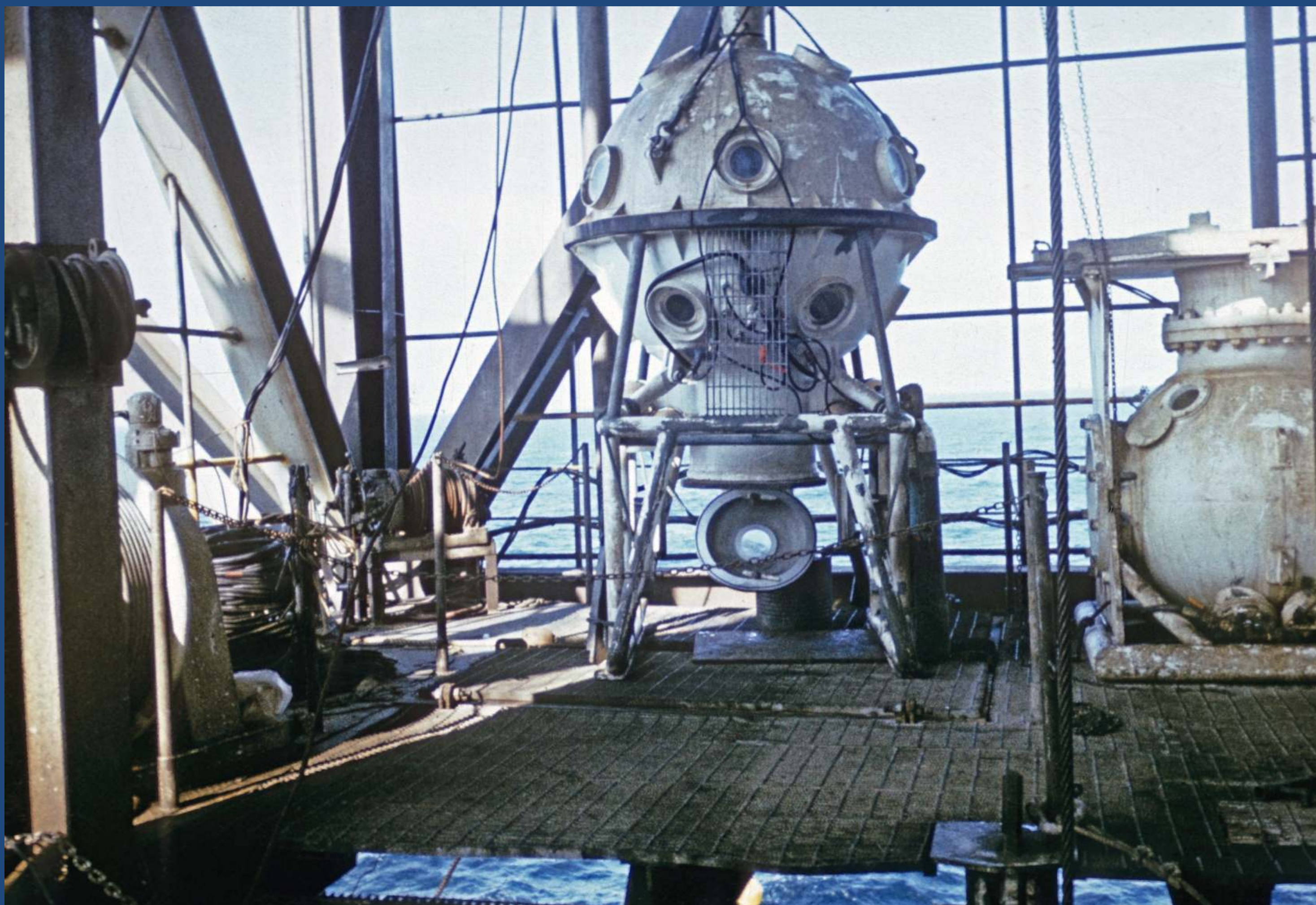

WELCOME ABOARD
M/V GLOMAR GRAND ISLE
LENGTH 400 FEET
BEAM 65 FEET
DEPTH 27 FEET
DISPLACEMENT 11,075 TONS
SPEED 12 KNOTS

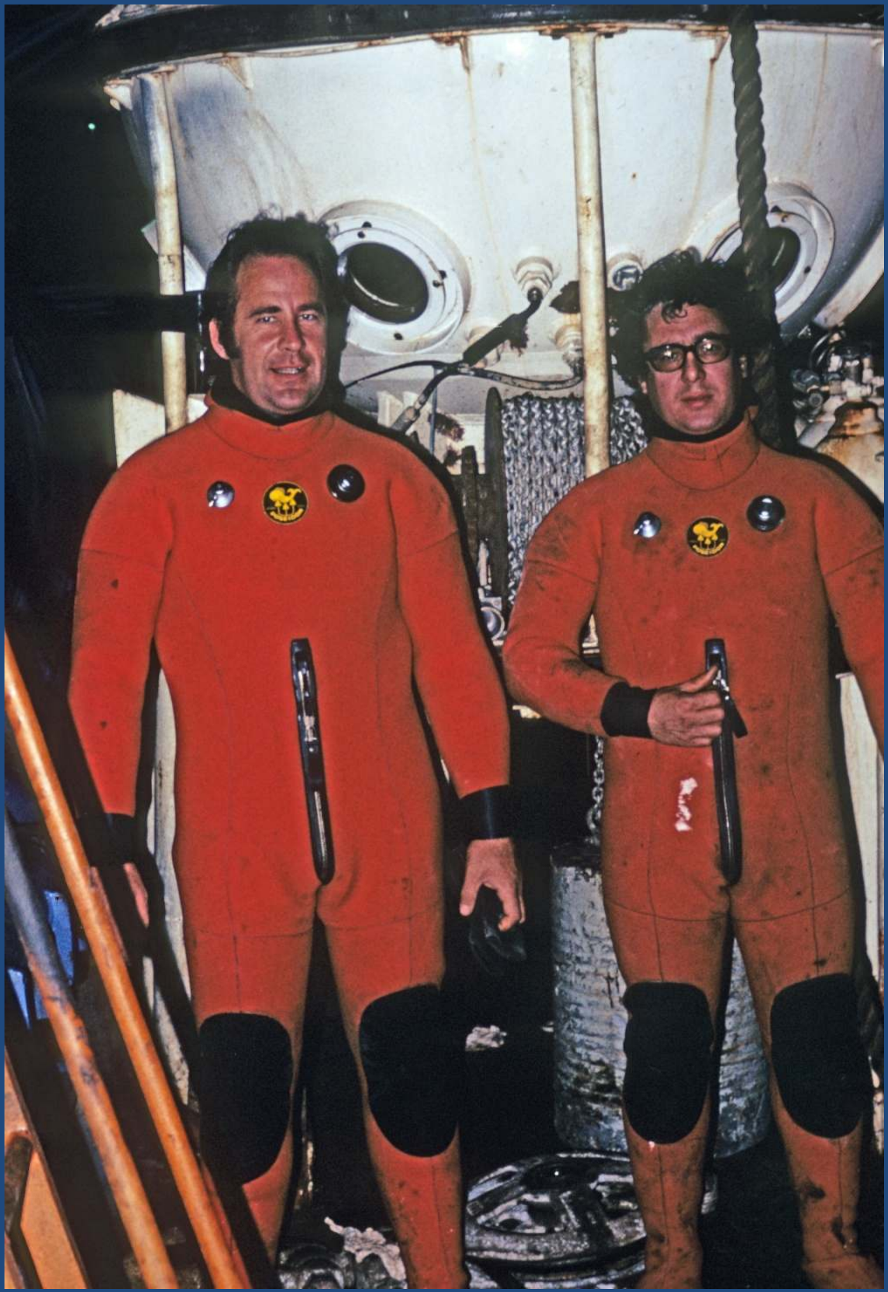
3 dives to 640 fsw on
Ne75 – O2 5%

6 divers total

Captain Claude Harvey on support
in the control shack

Readying the ADS IV for a dive





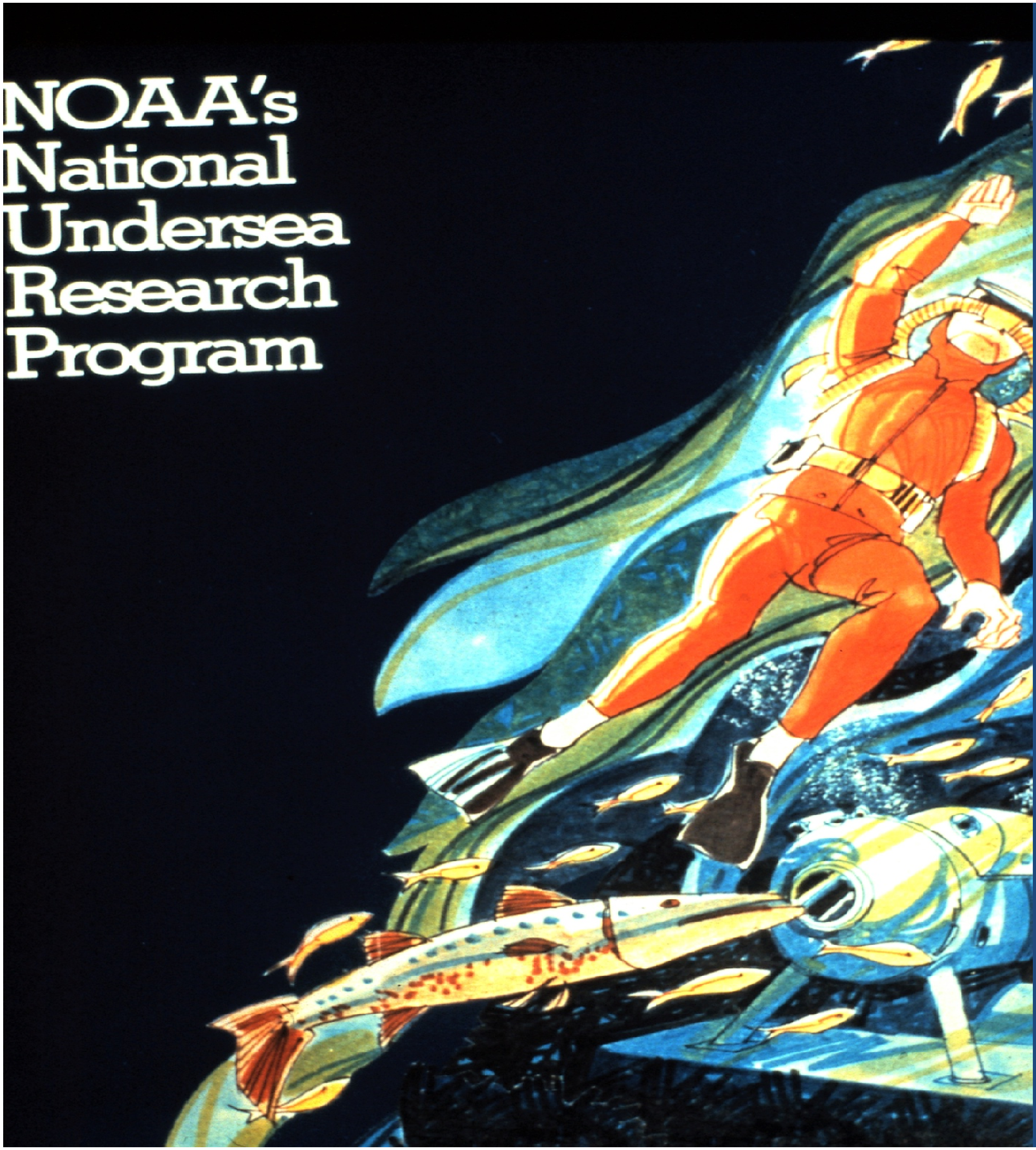
Divers Ready

for the plunge

to 640 fsw

on Crude Neon!

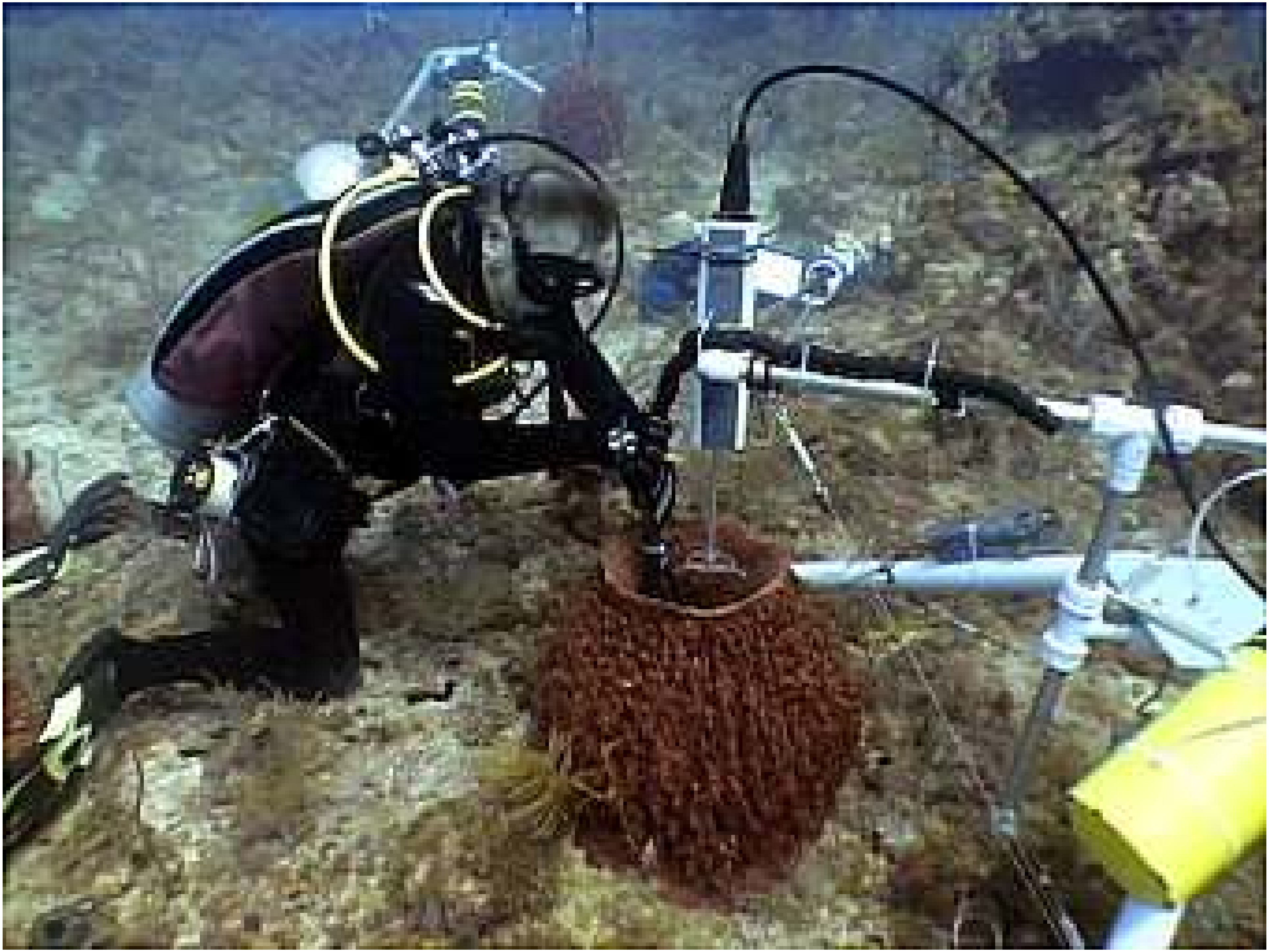
Divers and Crew supporting the Historic Dive!



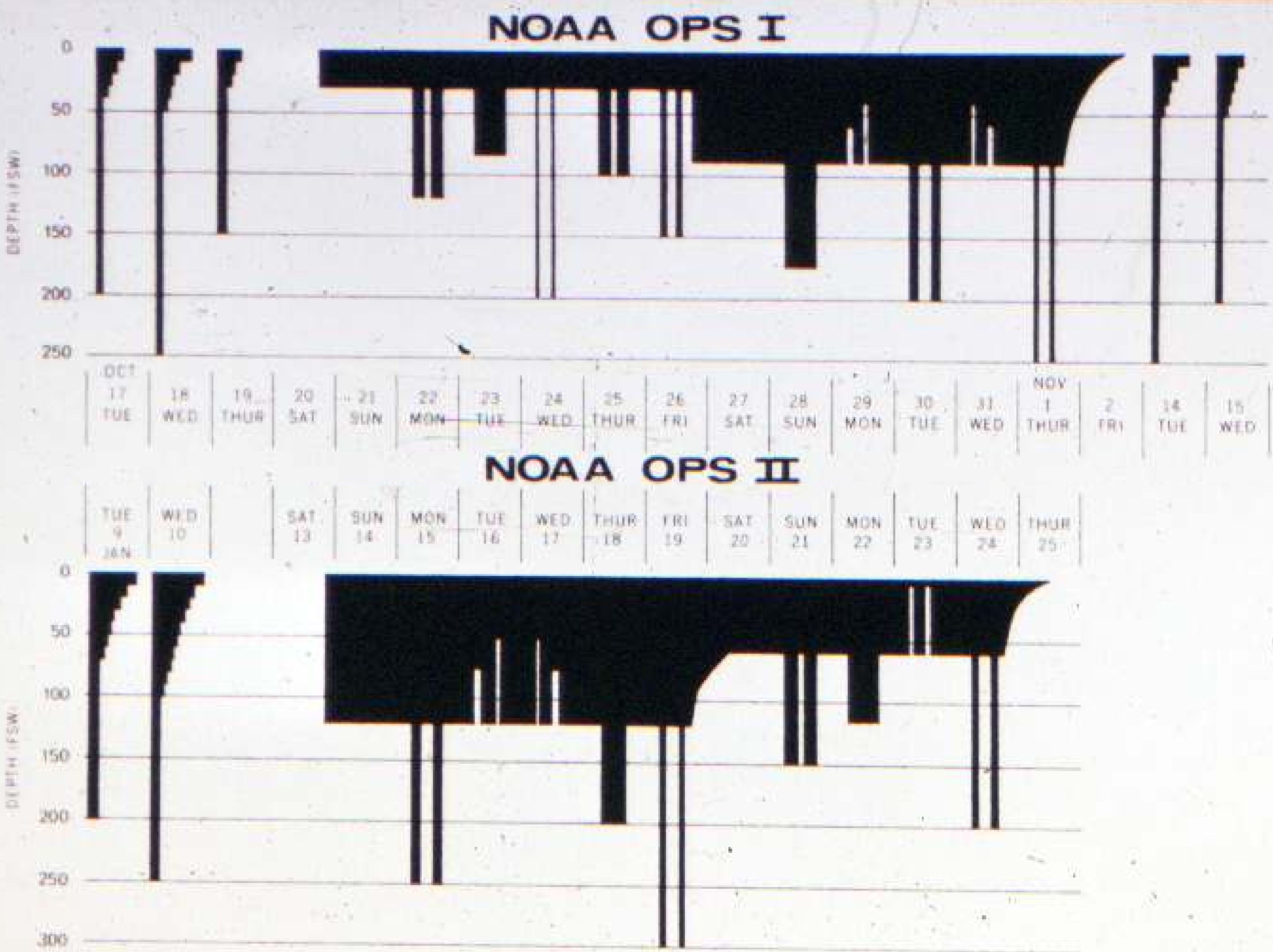
NOAA OPS

Needed to support

"Scientist in the Sea"



La Chalupa of the coast of Puerto Rico



NOAA OPS I
DEPTH (FSW)
0
50
100
150
200
250
OCT 17 TUE
18 WED
19 THUR
20 SAT
21 SUN
22 MON
23 TUE
24 WED
25 THUR
26 FRI
27 SAT
28 SUN
29 MON
30 TUE
31 WED
NOV 1 THUR
2 FRI
14 TUE
15 WED
NOAA OPS II
TUE 9 JAN
WED 10
SAT 13
SUN 14
MON 15
TUE 16
WED 17
THUR 18
FRI 19
SAT 20
SUN 21
MON 22
TUE 23
WED 24
THUR 25
DEPTH (FSW)
0
50
100
150
200
250
300

NOAA OPS II – circa 1972

60 fsw Saturation Pressure

Downward No-Decompression Dives – NOAA OPS II (1972)

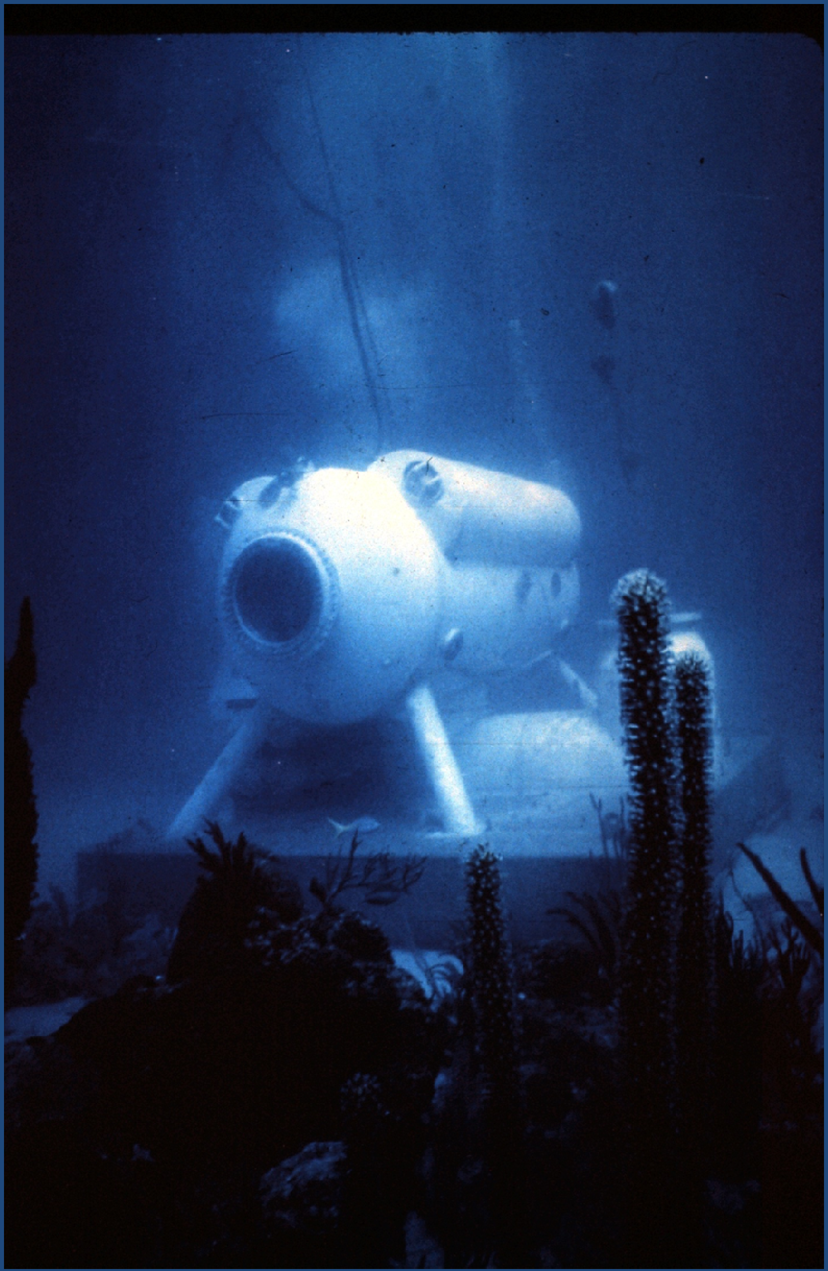
Habitat Depth fsw	Bottom Depth fsw	Pressure psi	Δ Depth fsw	Actual Bottom time minutes	USN Tables Bottom Time minutes
60 (1)	150	67	90	72	30
	150(2)	67	90	72	14
	115	51	55	347	60
	200	89	140	22	10
	200(2)	89	140	22	5

Note 1: 27 psi

Note 2: A second dive after a short habitat rest interval

De-Briefing and what's next ??

And of course, after every dive there must be a party



“Out at Sea”

Hydro-lab

Limitations to NOAA OPS

- Limitations to the bottom (working) time
- Only No-D tables were published
- No adjustment made for repetitive excursions
- Oxygen Limits needed better definition

Thus evolved the
"Repex" program

And from these early studies evolved practical uses for Diving Technology:

Tech diving

- With Hamilton Research's extensive background in Nitrogen based excursion diving (NOAA OPS I and II) we had requests for variations to "Air only" diving including He-O2 mixtures.

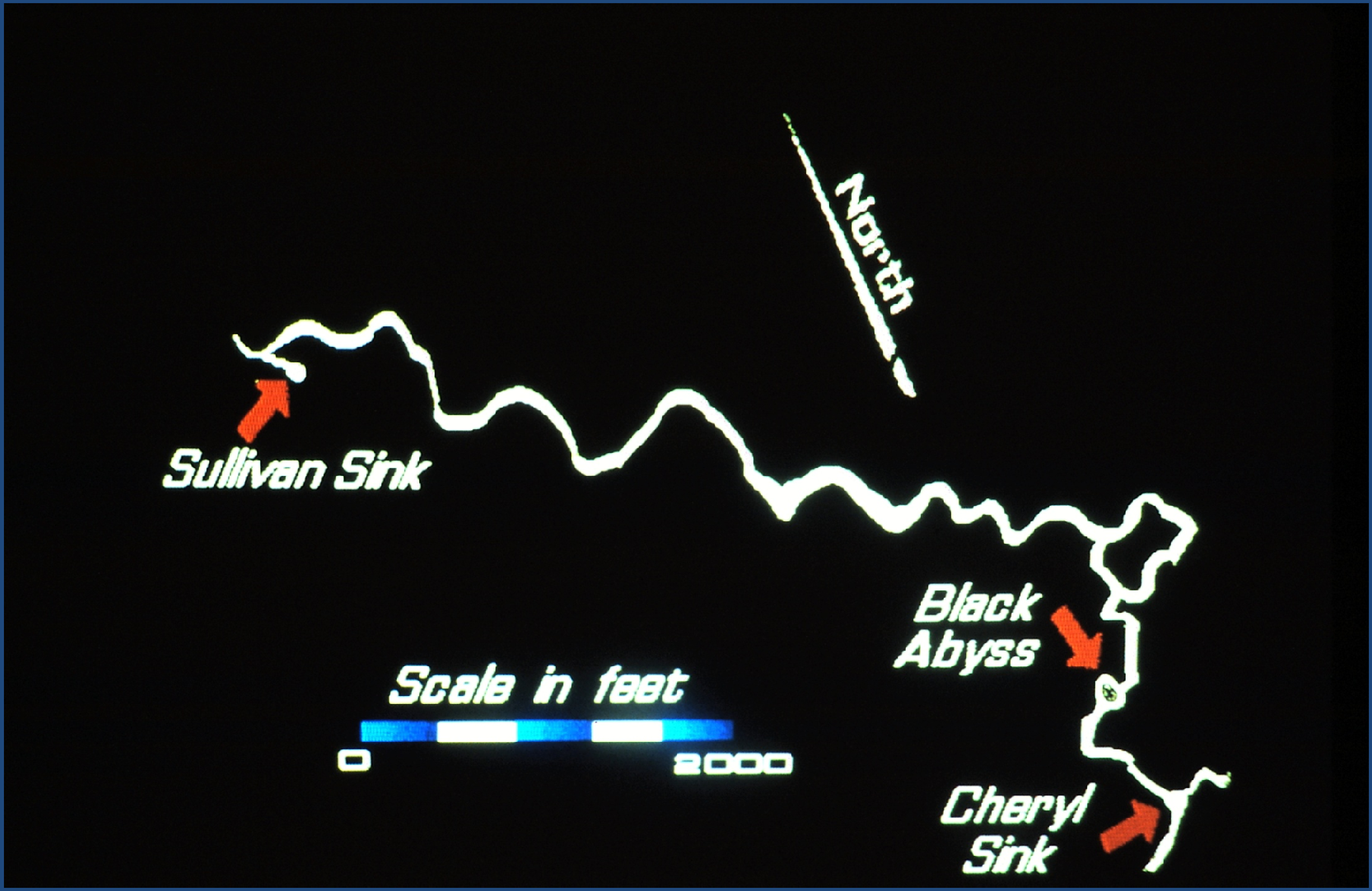
Cave Diving

Wakulla Springs State Park

Wakulla County, Florida

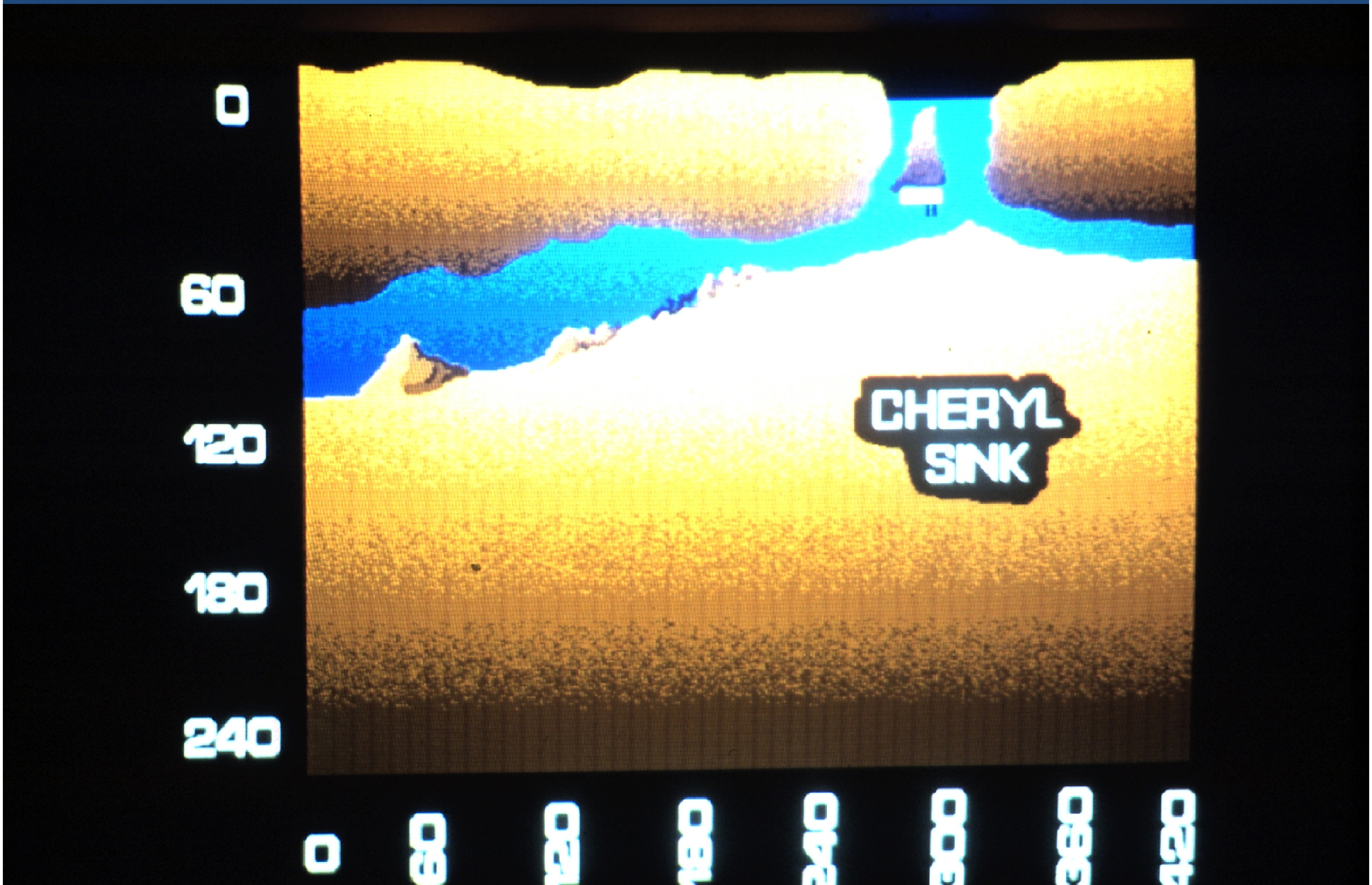
Cave Diving

Wakulla Springs State Park, Wakulla County, Florida



Technical Diving

- One definition is:
  "diving in which the diver changes the regulator (or the breathing mix)"
- Also, anytime a diver is not free to ascend, either there is an overhead ceiling or a decompression obligation
  – Cave diving was one interest that stimulated these developments


0
60
120
180
240
CHERYL SINK
0
60
120
180
240
300
360
420


O2PTIMA FX

Tech diver

Important effects of OEA

*“**O**xygen **E**nriched **A**ir”*

- Got away from **AIR** only
- Has a decompression component, if only to gain more no-stop time
  - That is, use of more O_2 in mix gave more no-stop time
- Highlighted the benefit of oxygen
- And it set the stage for **Technical Diving**
- This ultimately translated to deeper dives using Mixed Gases, including Helium/Nitrogen/Oxygen or “TriMix”

NASA needed help

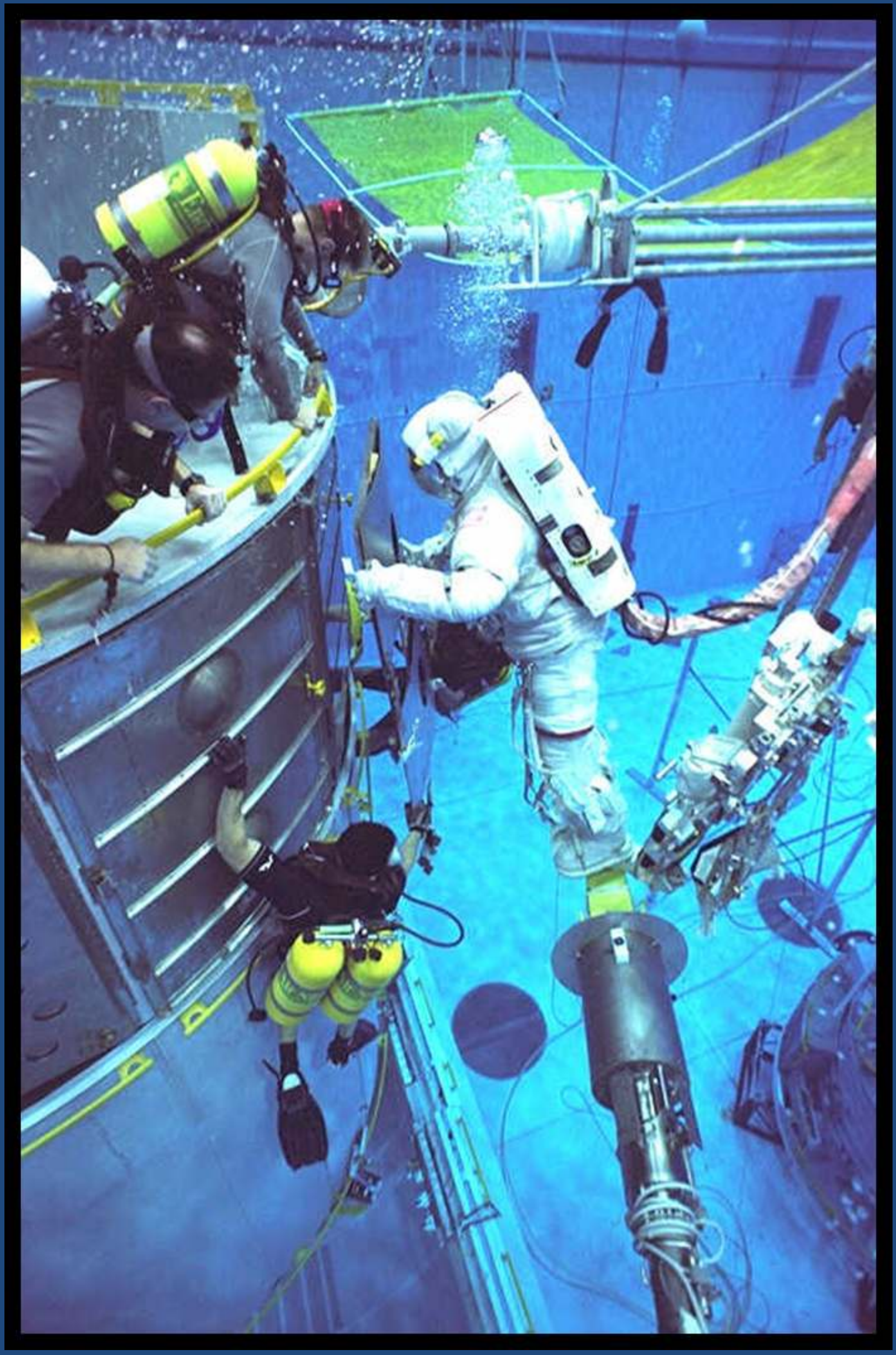
- The Hubble telescope had a slight Astigmatism”
- It needed repair!
- Up to this point “space walks” or EVA were limited to 2 hours.
- More time was needed to make the repairs; up to 8 hours.

NASA needed help

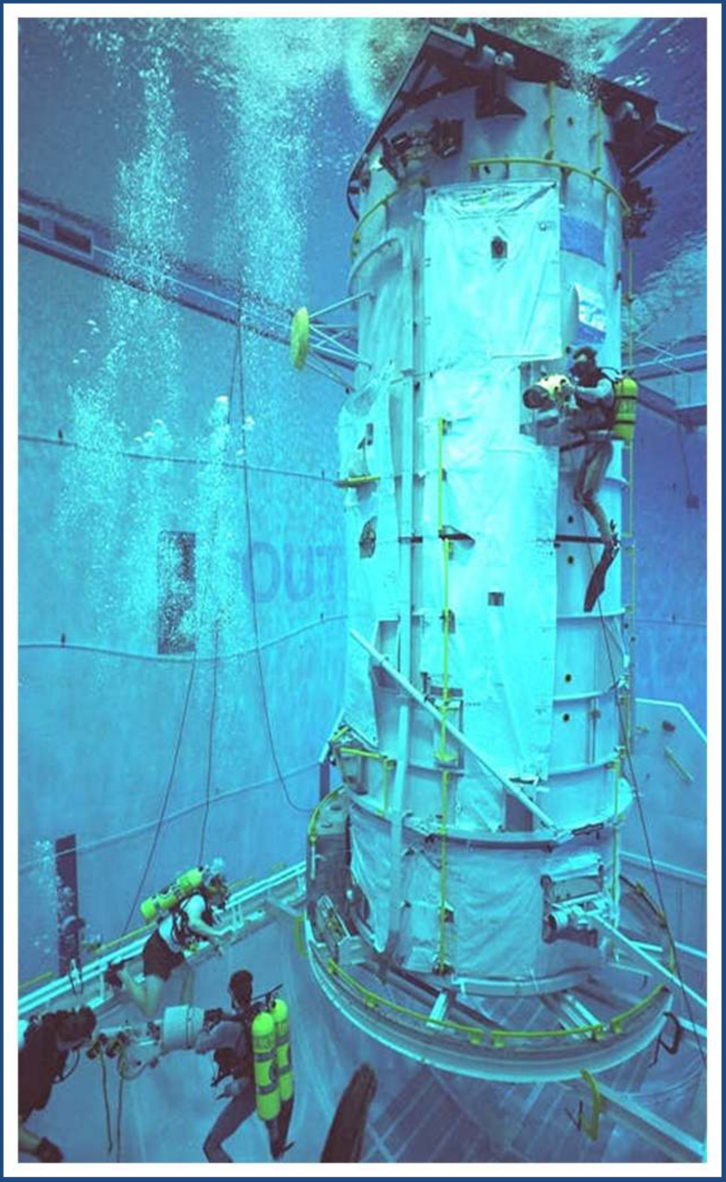
- EVA training in the neutral buoyancy tank was limited to air only, allowing approximately 2 hours of training.
- More and longer duration “zero-g” simulation training was required.
- Both the astronauts and the support divers need to spend longer durations underwater
- Mike Gerhardt, then with NASA, recommended the NOAA OPS and Technical Diving approaches for training dives.

Hamilton Research was called in!

- Bill Hamilton and colleagues developed procedures to extend the “zero-g” training.
- Exposure and Decompression procedures were developed using OEA.
- Astronauts and support divers now use 46% Oxygen in a balance of Nitrogen.
- These procedures are directly applicable to Deep tunneling and the extreme exposure times during shallow tunnels.



NASA's "neutral buoyancy" tank uses OEA mixtures at pressure and during decompression



S109E5733

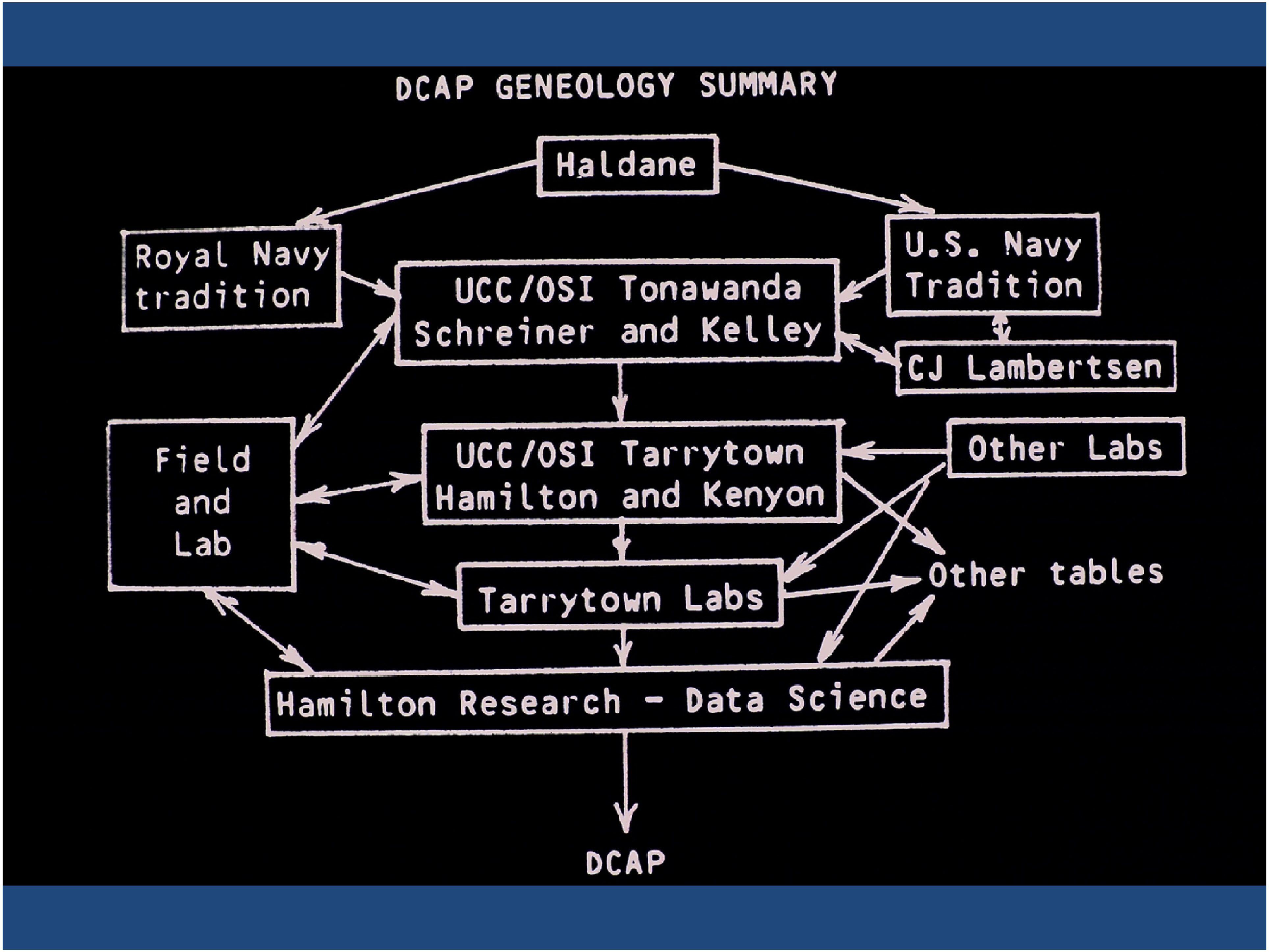
Other Projects
NASA support – “Flying after diving”

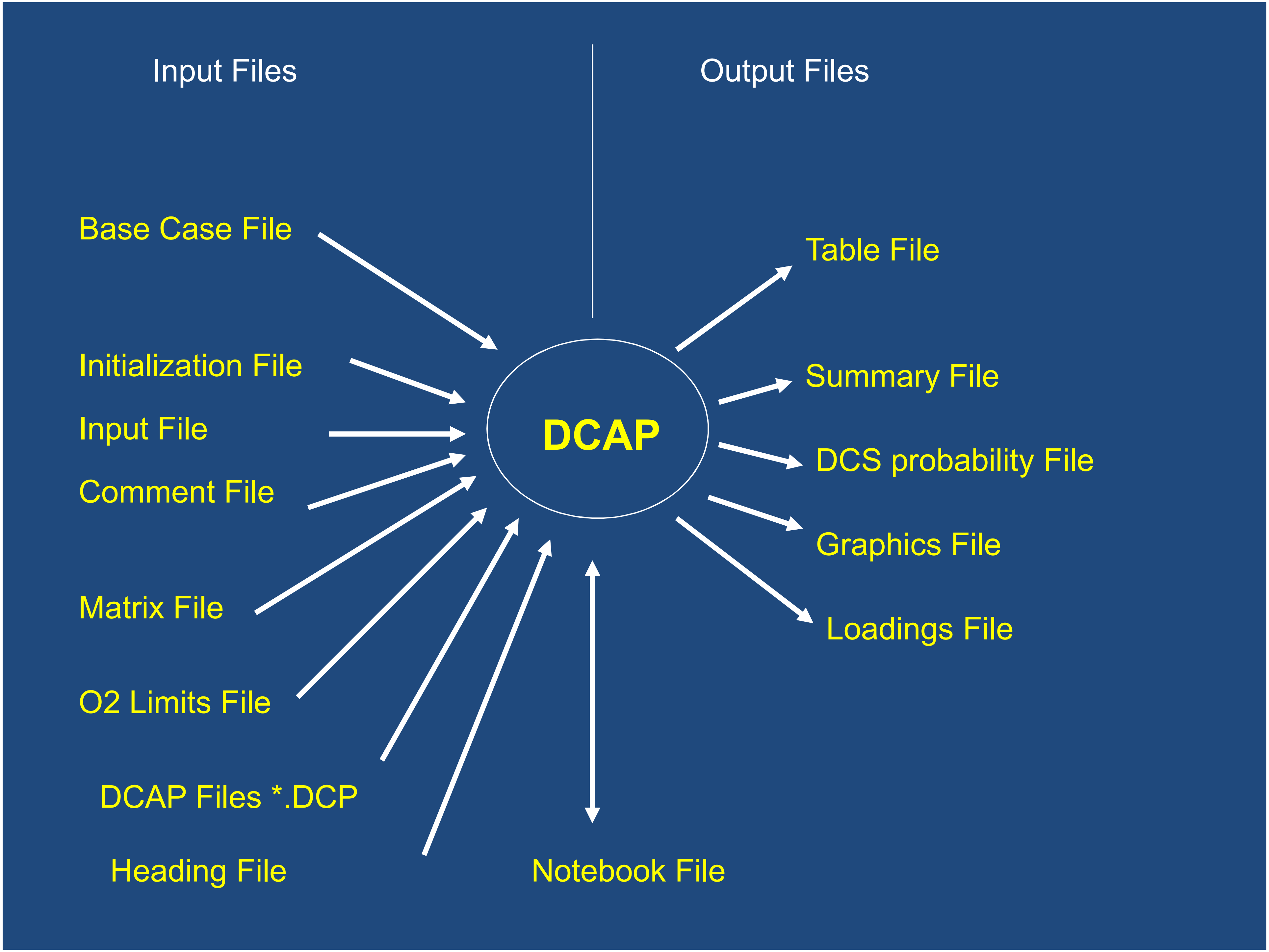
We needed a way to be able to practically solve all the various combinations of Hyperbaric and Hypobaric exposures problems that we and our clients encountered.

A "Decompression Computation and Analysis" Tool was required

What is DCAP

- A comprehensive Hypobaric/Hyperbaric Programming Tool
- Decompression Profile Development
- Profile Analysis
- Decompression Table Publishing
- Used by Engineers, Physiologists, Researchers, Dive Operations Personnel
  - No need to be a programmer


DCAP GENEOLOGY SUMMARY
Haldane
Royal Navy tradition
U.S. Navy Tradition
UCC/OSI Tonawanda Schreiner and Kelley
CJ Lambertsen
Field and Lab
UCC/OSI Tarrytown Hamilton and Kenyon
Other Labs
Other tables
Tarrytown Labs
Hamilton Research - Data Science
DCAP


Input Files
Output Files
Base Case File
Initialization File
Input File
Comment File
Matrix File
O2 Limits File
DCAP Files *.DCP
Heading File
DCAP
Notebook File
Table File
Summary File
DCS probability File
Graphics File
Loadings File

Statement File

- User Defined “Base Case” Statement
- 24 Statements (2004)
- 2 + EXCURSION (modified BOTTOM) added in 2005
- Others can be added with HRL help
- There are 5 classes of Statements
  - Definition e.g. SET, MIX & COMMENT
  - FILE e.g. MATRIX INIT, HEADING, NOTEBOOK, etc.
  - Control e.g. POSITION, DECOMPRESS, ASCEND
  - DCAP specific e.g. BASECASE, END, PROFILE
  - Conditional e.g. IF and IF.ONCE
- Instructs DCAP how to next proceed

```
 BASE.CASE    Dair00.h00
C             This "Base Case" is a simple air profile
 PURPOSE      Air development.  Test TON-II algorithm.  Air, Basic 170/30
              fsw/min table, instant compr, air matrix, factors are:
              Initial Ascent is 30 fsw/min, Ascent after 1st Stop is 10 fsw/min.
 INIT          FILE=If1101.Dcp
 SET          TITLE=Air test
               AUTHOR=rwh/djk
               BOTTOM.DEPTH=170
               BOTTOM.TIME=30
               TABLE.FORMAT=1
 MODEL         TON-II
 HEADING        FILE=HUBM00.BUL
 NOTEBOOK       FILE=Nair00.DCP
 MATRIX         FILE=Mf11F6.DCP
 MAX.MODEL      FILE=airmodel
 MIX            1=Bagmix
                2=AIR O2=20.9 % N2=100 BALANCE%
 COMMENT        FILE=CMAO00.AIR
 IF.ONCE        CURRENT.DEPTH=0 AND DECOMPRESSING THEN COMMENT=44
                FIRST.STOP THEN RATE=10
 PROFILE
 POSITION        DEPTH=0 RATE=0 STOP=0 TRAVEL=0 MIX=2 COMMENT=2
 BOTTOM         RATE=0 TRAVEL=0 COMMENT=8
 DECOMPRESS  DEPTH=0 RATE=30
 END
```

Air test
rwh/djk 04Nov30
Dair00.h00 Mf11F6.DCP

DEPTH	170 FSW
BOTTOM TIME	30 MIN
BOTTOM MIX	AIR
BOTTOM PO2	1.29 ATM

Time in minutes

DEPTH FSW	STOP TIME	DEC TIME	MIX	HIPO2 ATM	COMMENTS
00	00	00	AIR	0.21	Begin descent on air
170	30	00	AIR	1.29	decompress to first stop at 30 fsw/min
60	01	05	AIR	0.59	ascent rate now 10 fsw/min
50	02	08	AIR	0.53	
40	03	12	AIR	0.46	
30	09	22	AIR	0.40	
20	25	48	AIR	0.34	
10	50	99	AIR	0.27	
00	00	100	AIR	0.21	Reach surface

TOTAL TIME = 02:10 HR:MN
DECOM TIME = 01:40 HR:MN
OTU = 47 VC DROP =-0.3%

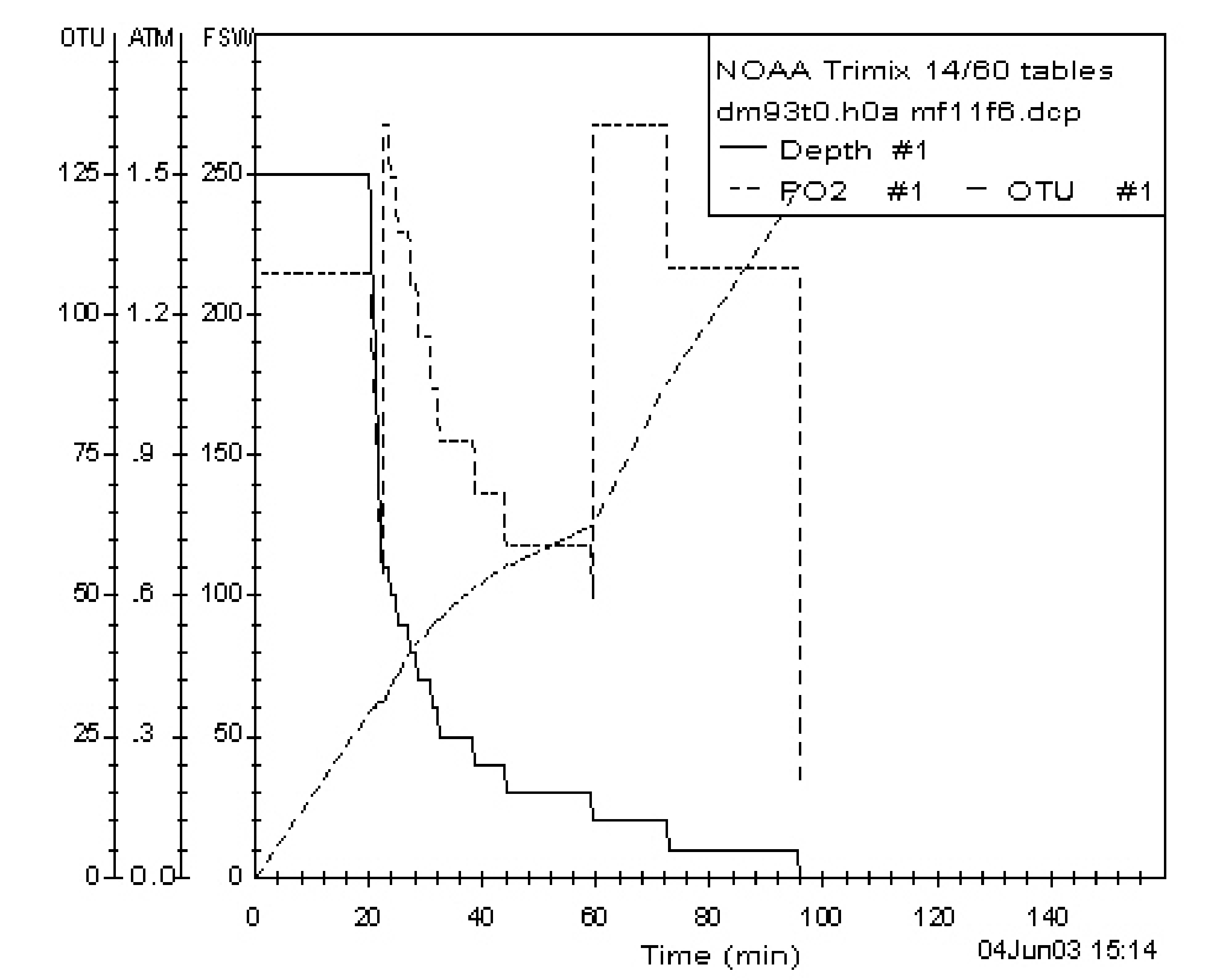
Air test
rwh/djk 04Nov30
Dair00.h03 Mf11F6.DCP

DEPTH 170 FSW
MIX AIR
PO2 1.29 ATM

============Condensed table, stop and total decomp. times, min============

Bottom time min	<------Stop Depths------> 90	80	70	60	50	40	30	20	10	Decomp time min
30				01	02	03	09	25	50	100
35				02	02	07	10	35	63	129
40			01	01	05	08	21	35	75	156
45			01	02	08	08	29	39	82	179
50			01	05	08	14	32	50	95	215
60			04	07	08	28	32	67	117	273
70		01	07	07	21	28	45	73	152	345
80		04	07	13	26	28	59	90	168	406
90		06	07	22	26	37	63	103	197	472
100	01	06	13	24	26	49	66	125	219	541
120	03	11	22	24	39	56	90	149	268	674

DCAP graphics



DCAP used for tunneling

- MTA "East Side Access" – NYC
- Brightwater East Trimix – Seattle, WA

.

. . . . . *Future projects* . . . . . .

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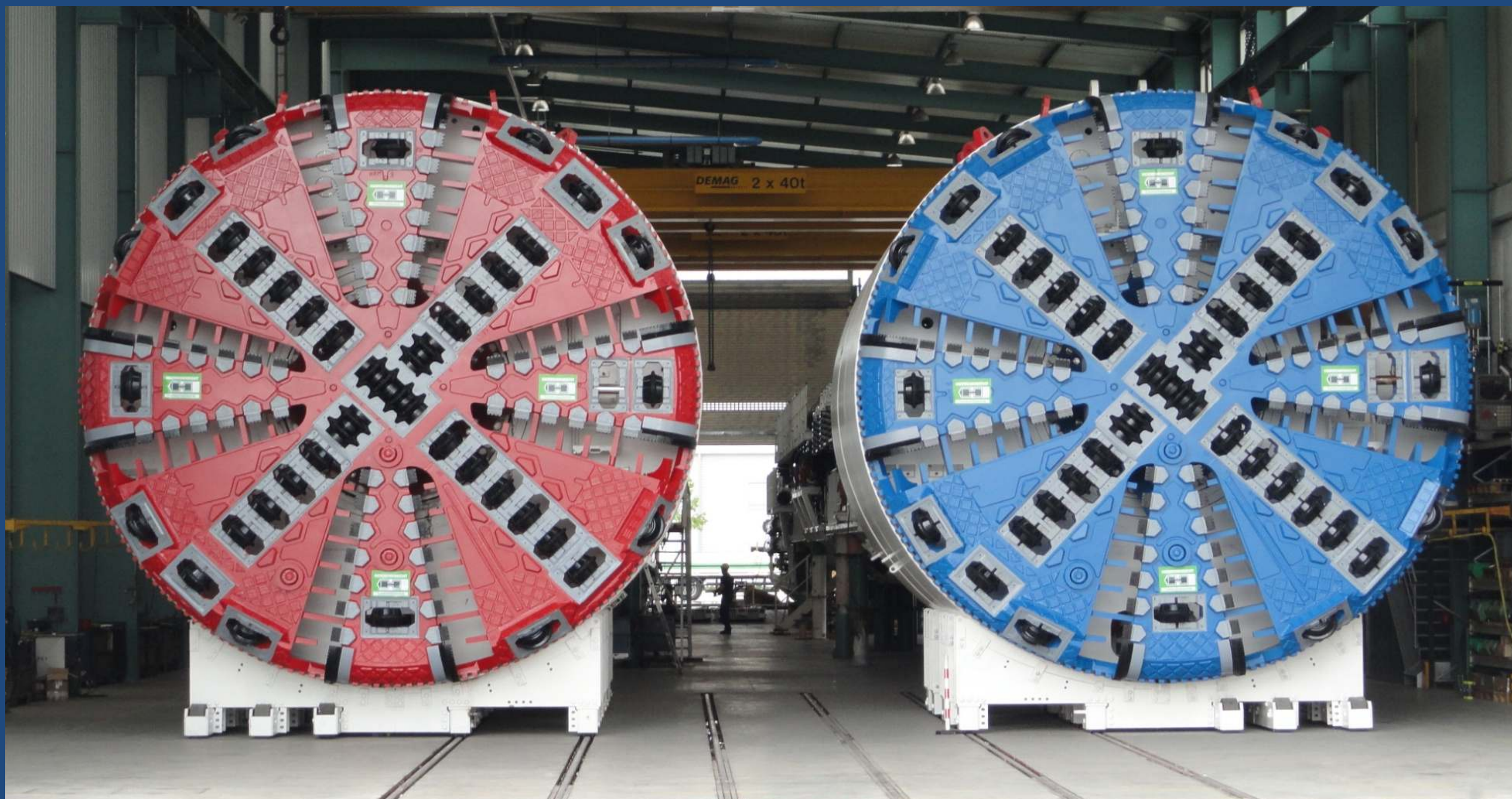
- Exploratory Excursions from Saturation
- The use Crude Neon as replacement for Helium

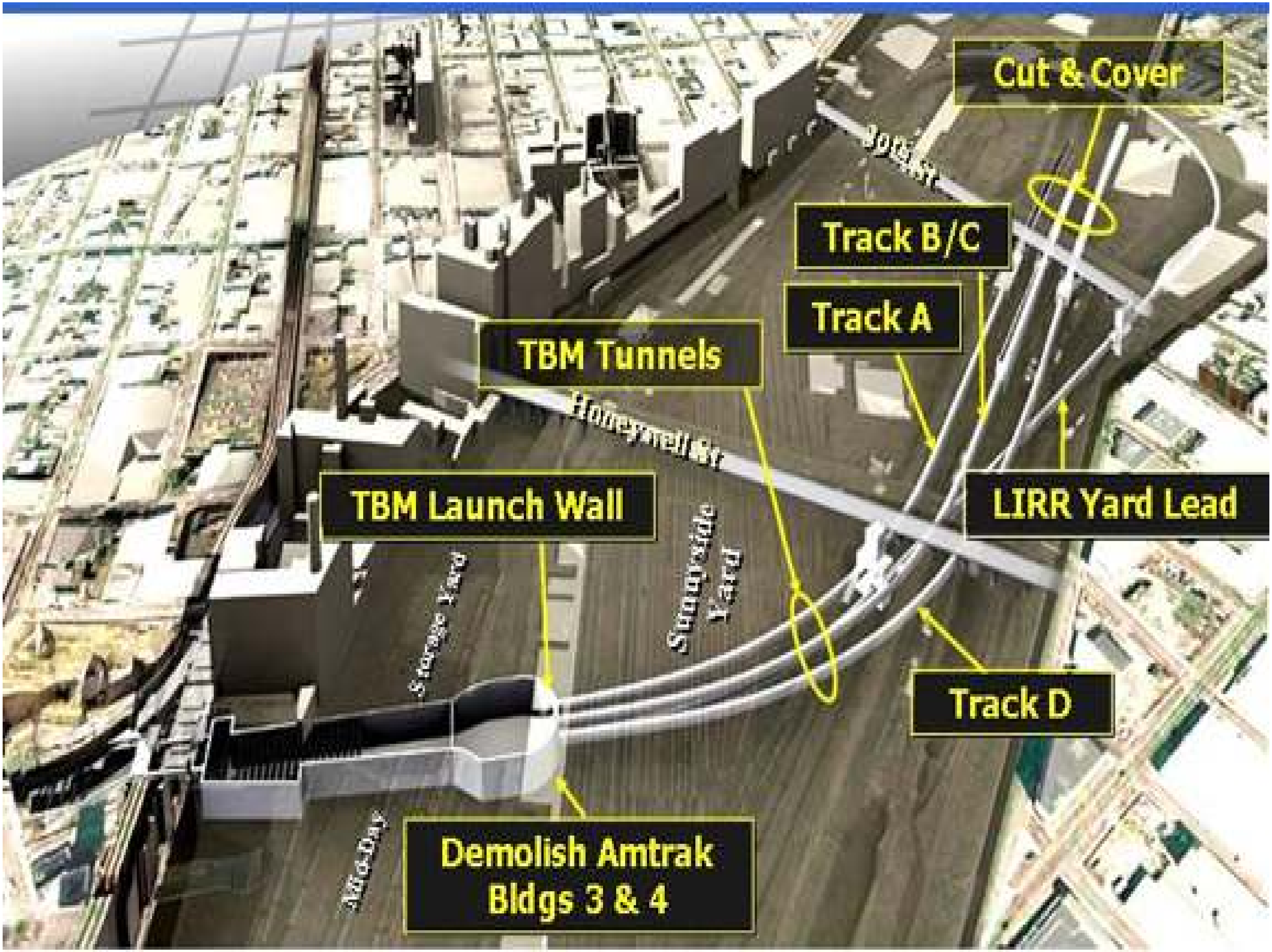
Hyperbaric Tunneling
East Side Access - New York City



The Project

- Expansion of LIRR service to Grand Central Terminal.
- Largest transportation project in the country.
- 8 billion dollar project.
- Scheduled for completion in August 2019.

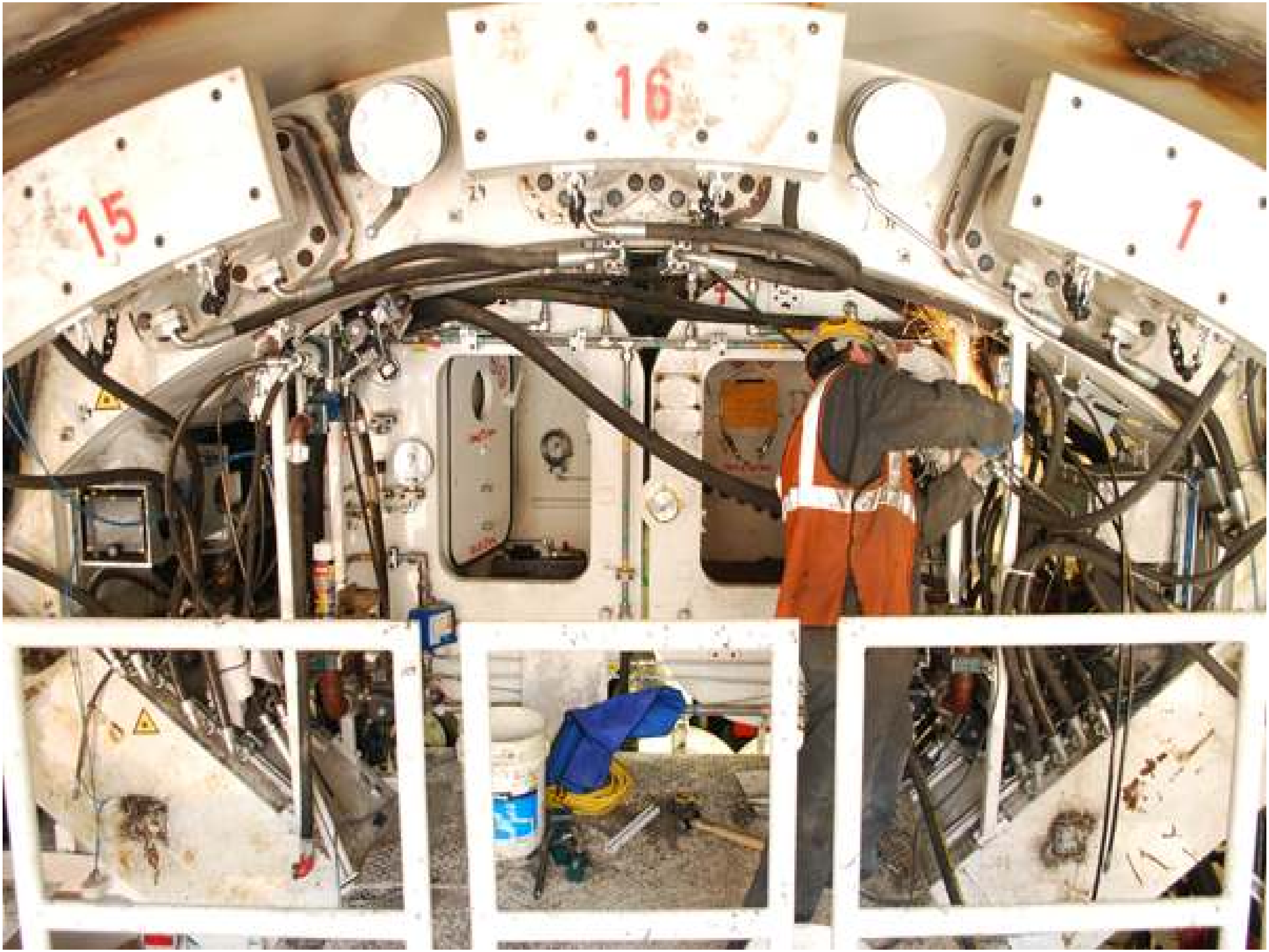
Central Park
Metro-North Railroad
8,600ft
(17,200 Linear Ft.)
63rd Street Tunnel
63rd St
41st Ave
Queensborough Bridge
5,500ft.
(11,200 Linear Ft.)
Sunnyside Yard
Northern Blvd
AMTRAK
LIRR
Port Washington Branch
29th Ave
25A
25
Queens Blvd
Mid-Day Storage Yard
Harold Interlocking
QUEENS
Roosevelt Island
7,200ft.
(24,000 Linear Ft.)
53rd St
Arch Street Yard & Shop Facility
Grand Central Terminal
42nd St
Long Island Expressway
495
Queens-Midtown Tunnel
LIRR
Montauk Branch
38th St
MANHATTAN
EAST RIVER
BROOKLYN
5th Ave.
Madison Ave.
Park Ave.
Lexington Ave.
3rd Ave.
2nd Ave.
Legend
Existing LIRR Tunnel Structure - (17,200 LF)
Tunnel Structure to Be Built - (35,200 LF)

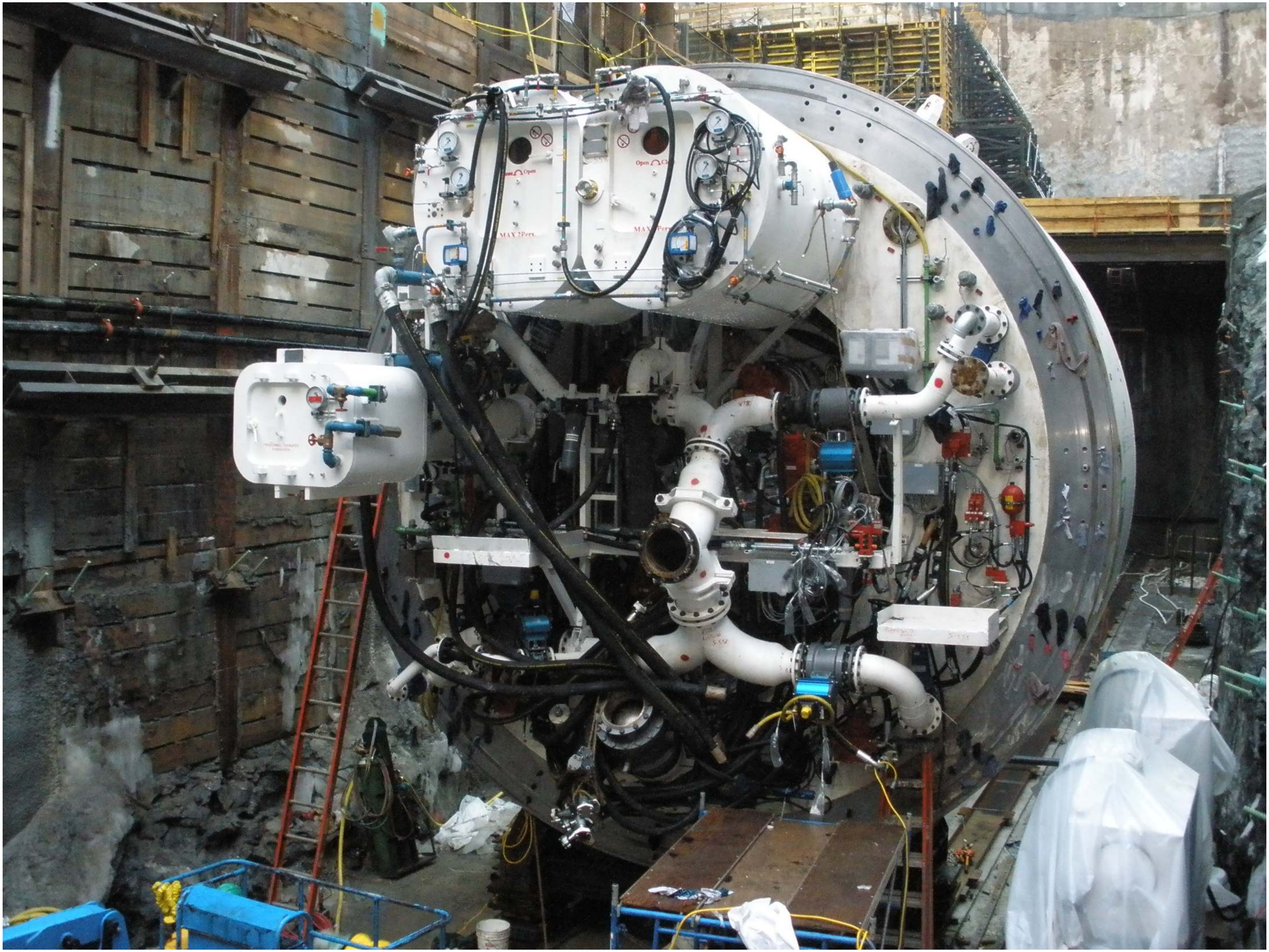


Cut & Cover
Track B/C
Track A
TBM Tunnels
TBM Launch Wall
LIRR Yard Lead
Sunnyside Yard
Storage Yard
Track D
Demolish Amtrak Bldgs 3 & 4

MTA – GTF East Side Access

- Totaling 382 interventions managed by Life Support Technologies
- 44 man days, 2 hours, and 14 minutes (time under pressure)
- An average of 2 hours and 46 minutes per intervention; pressures between 18 and 34 psi
- <240 min intervention time
- 3 (normal), occasionally 4 man work crews
- No decompression incidents


15
16
1



“Breaking through”

MTA – GTF East Side Access

- Decompression Rate is -4 psi/minute.
- Breathe Oxygen during decompression starting at the first stop.
- Air breaks (up to 5 min) not included in the decompression stop times.
- Travel not included in stops but is in totals.
- Source Dqoktz.h2c & Mp11f6.psi.

Mp11f6.psi

compartment # and halftimes

	1	2	3	4	5	6	7	8	9	10	11
N2	5	10	25	55	9	145	200	285	385	520	670
He	5	10	20	40	60	80	100	130	160	200	240
H2	5	10	20	45	70	110	150	205	270	360	455
Ne	5	10	20	40	65	85	110	145	180	225	275

M values

BASE	40.5	31.1	22.9	16.9	15.5	15.3	15.1	15.1	15.1	15.1	14.9
SLOPE	1.30	1.05	1.08	1.06	1.04	1.02	1.01	1.00	1.00	1.00	1.00

Sample Table – MTA “East Side Access” 40 psi AIR / O2 decompression

Exposure time	Time to 1st stop	Decompression stop pressures, psi. Stop Times in minutes / Breathe Oxygen at all stops										Total deco time	Total time
min	min	**20**	**18**	**16**	**14**	**12**	**10**	**8**	**6**	**4**	**2**	min	min
30	9.5										8	18	48
45	8.5								5	7	9	31	76
60	7.5						1	6	7	8	13	45	105
75	7.0					2	6	6	7	10	17	58	133
90	6.5				2	5	6	6	9	14	16	68	158
105	6.0			1	5	5	6	7	12	15	18	79	184
120	6.0			4	5	6	6	10	13	14	23	91	211
135	5.5		2	5	5	5	8	12	13	17	25	102	237
150	5.5		4	5	5	6	11	12	13	21	28	115	265
165	5.0	2	4	5	5	9	11	12	15	22	32	127	292
180	5.0	3	4	5	7	10	11	12	18	23	35	138	318
195	5.0	4	5	4	9	11	11	13	20	26	35	148	343
210	5.0	6	4	7	9	11	11	16	20	29	36	159	369

Standard Air with O2 Decompression

GTF East Side Access TBM Tables — **32 psi**

12Jan14 — **AIR**

PO2 0.66 atm

Exposure time	Time to 1st stop	Decompression stop pressures, psi. Stop Times in minutes — Breathe Oxygen at all stops										Total deco time	Total time
min	min	**20**	**18**	**16**	**14**	**12**	**10**	**8**	**6**	**4**	**2**	min	min
30	8.0											8	38
45	7.0									2	8	18	63
60	6.5								3	7	9	27	87
75	6.0							2	7	8	12	37	112
90	5.5						1	6	7	9	16	47	137
105	5.5						5	6	7	13	16	55	160
120	5.0					2	6	6	10	14	16	62	182
135	5.0					5	6	6	13	14	19	71	206
150	4.5				1	6	6	9	13	14	23	80	230
165	4.5				3	5	6	12	13	16	25	88	253
180	4.5				4	6	8	12	13	19	27	97	277
195	4.5				5	6	11	12	13	21	30	106	301
210	4.0			1	5	8	11	12	15	22	32	114	324

- Decompression Rate 4 psi/minute
- Breathe Oxygen during decompression starting at the first stop
- Air breaks (up to 5 min) not included in the decompression stop times
- Travel not included in stops but is in totals
- Source Dqoktz.h2c & Mp11f6.psi

- PSI not FSW
- Green indicates oxygen breathing
- Oxygen breathing :25, then :05 Air break.
- Compression rate included in Exposure time

Extending Air with DCAP

Extensions of GTF MTA tables to cover the range from 40 psi to 72 psi

but

Change the Rate of Ascent

Air with Oxygen Decompression

- Air a working pressures
- Initial decompression rate of -10 psi/min
- Change rate to -5 psi/min at the first stop
- O2 breathing starting at 20 psi
- Change rate of depressurization to -1 psi/min

Air with Oxygen Decompression

"extending the MTA GTF tables"

Pressure (psig)	Working time (minutes)	Decompression time (minutes)	Intervention time (minutes)
34	**177**	**63**	**240**
50	**136**	**104**	**240**
72	**90**	**150**	**240**

Tech diving is Decompression Related

- Focused on deeper dives, which has to involve decompression
- Clever and detailed application of decompression techniques
- Oxygen is paramount
  - We have to learn what it does for decompression
  - We have to tolerate its toxicity

Important effects of OEA

- Got away from AIR only
- Has a decompression component, if only to gain more no-stop time
  - That is, use of more O_2 in mix gave more no-stop time
- Highlighted the benefit of oxygen

  (So we call in **Nitrox**)
- And it set the stage for **Technical Diving**
- Technical diving changes everything

Optimizing the Air tables with OEA (Oxygen Enriched Air)

- Use Higher percentage Oxygen in Air at pressure
- Use Higher percentage Oxygen during decompression

Percent Oxygen for Various Partial Pressures (atm)

Intervention Pressure psi	1.2	1.3	1.4
20	51	55	59
25	44	48	52
30	39	43	46
35	35	38	41
40	32	35	38
45	30	32	34
50	27	30	32
55	25	27	30
60	24	26	28
65	22	24	26
70	21	23	24
75	20	21	23
80	19	20	22
85	18	19	21

OEA 50, 50% Oxygen, Balance Nitrogen

OEA 38, 38% Oxygen, Balance Nitrogen

OEA 32, 32% Oxygen, Balance Nitrogen

OEA 26, 26% Oxygen, Balance Nitrogen

Open circuit surface supplied

- Simple systems, use of a band mask.
- Easy to use and understand.
- Cover both mouth and nose internally.
- Would allow the diver to communicate (via an internal microphone).
- Gas cost would be higher than with a re-breather system.

Kirby Morgan
KMB-8
Band Mask

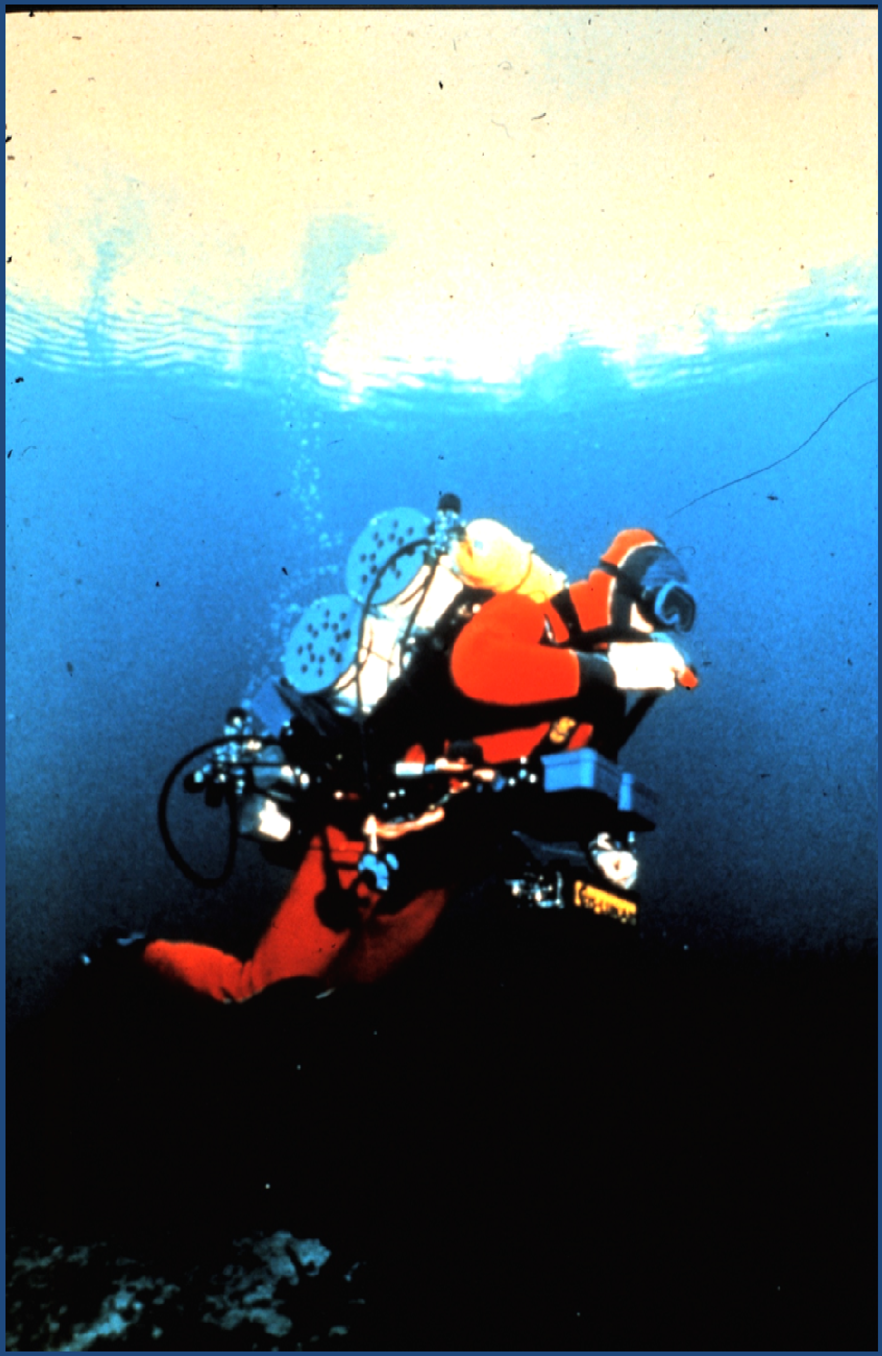
Diver preparing for an ergometer run in one of the Purisima spheres.

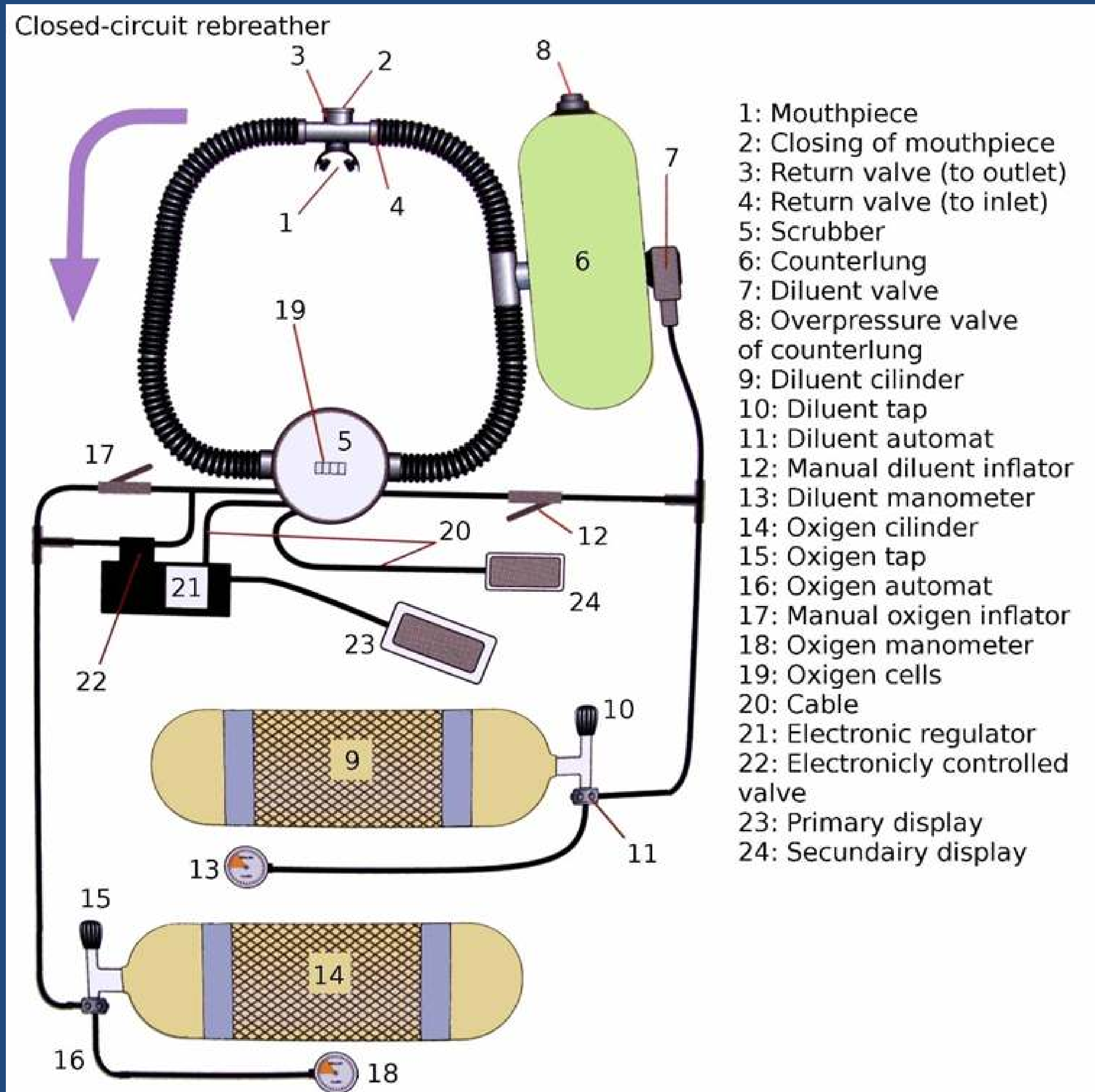
Band Masks are now being used in tunneling, but awkward.

A lighter more flexible band Mask is needed for tunneling!

Use of a Constant PO_2 Rebreather System

Total decompression time is optimized by maintaining a constant PO_2 during decompression




Closed-circuit rebreather
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
1: Mouthpiece
2: Closing of mouthpiece
3: Return valve (to outlet)
4: Return valve (to inlet)
5: Scrubber
6: Counterlung
7: Diluent valve
8: Overpressure valve of counterlung
9: Diluent cilinder
10: Diluent tap
11: Diluent automat
12: Manual diluent inflator
13: Diluent manometer
14: Oxigen cilinder
15: Oxigen tap
16: Oxigen automat
17: Manual oxigen inflator
18: Oxigen manometer
19: Oxigen cells
20: Cable
21: Electronic regulator
22: Electronicly controlled valve
23: Primary display
24: Secundairy display

CIS-LUNAR
DEVELOPMENT LABORATORIES

MK-5P

Summary

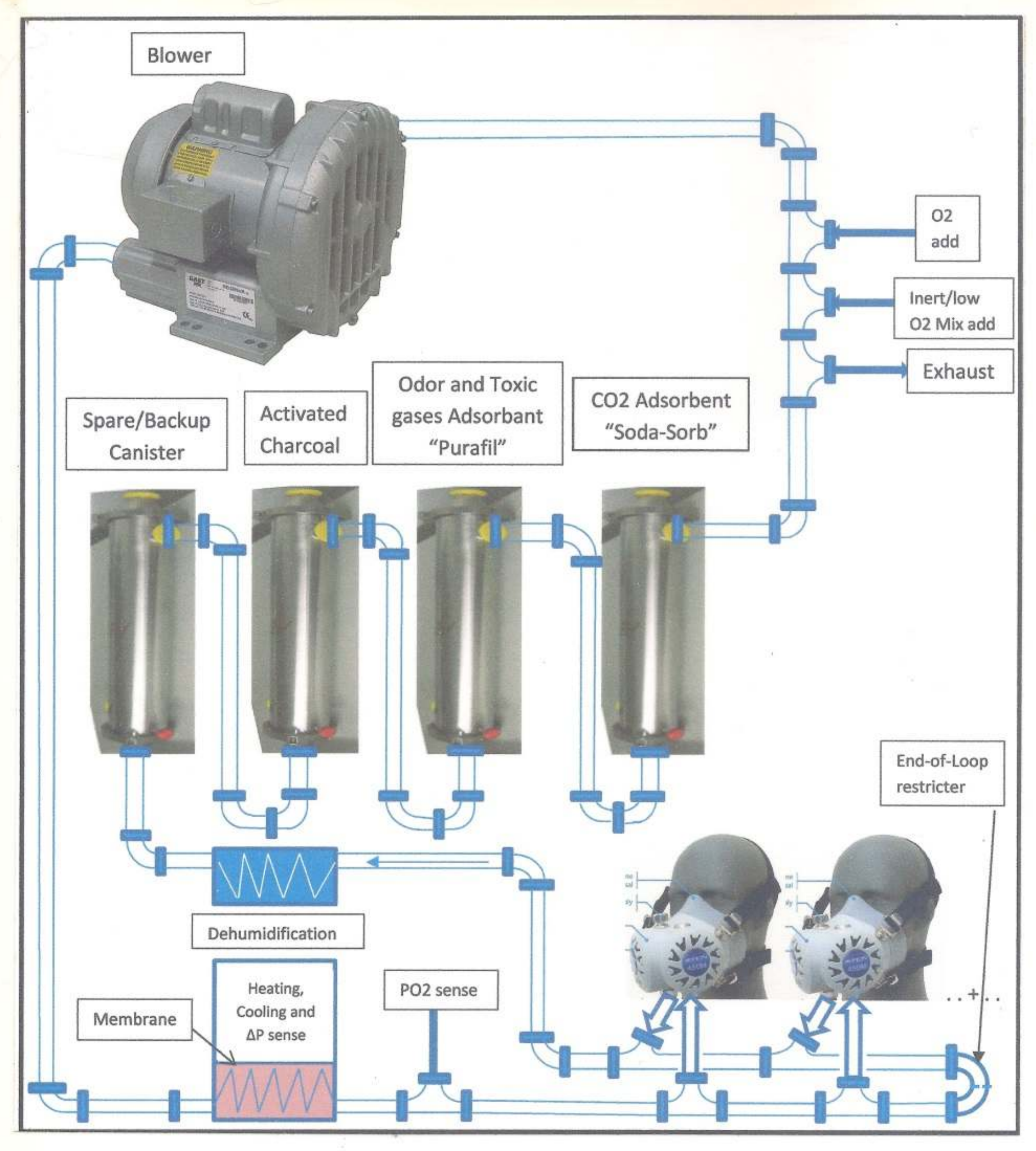
- Closed-Circuit, Mixed-gas
- 6-12 hr duration
- 500 fsw capability
- Real-time DCAP (New version now being made in Sweden)

Slide by Richard Pyle

Classical Re-breathers are cumbersome for Tunnel workers

- The back pack of a typical re-breather is too big and bulky for working in the “bubble” near the head.
- A mask would be need to communicate rather than a simple mouthpiece.
- A hybrid operation may be warranted:
  - Simple open circuit while at the head
  - Closed circuit during decompression

Need a "Recirculating" system



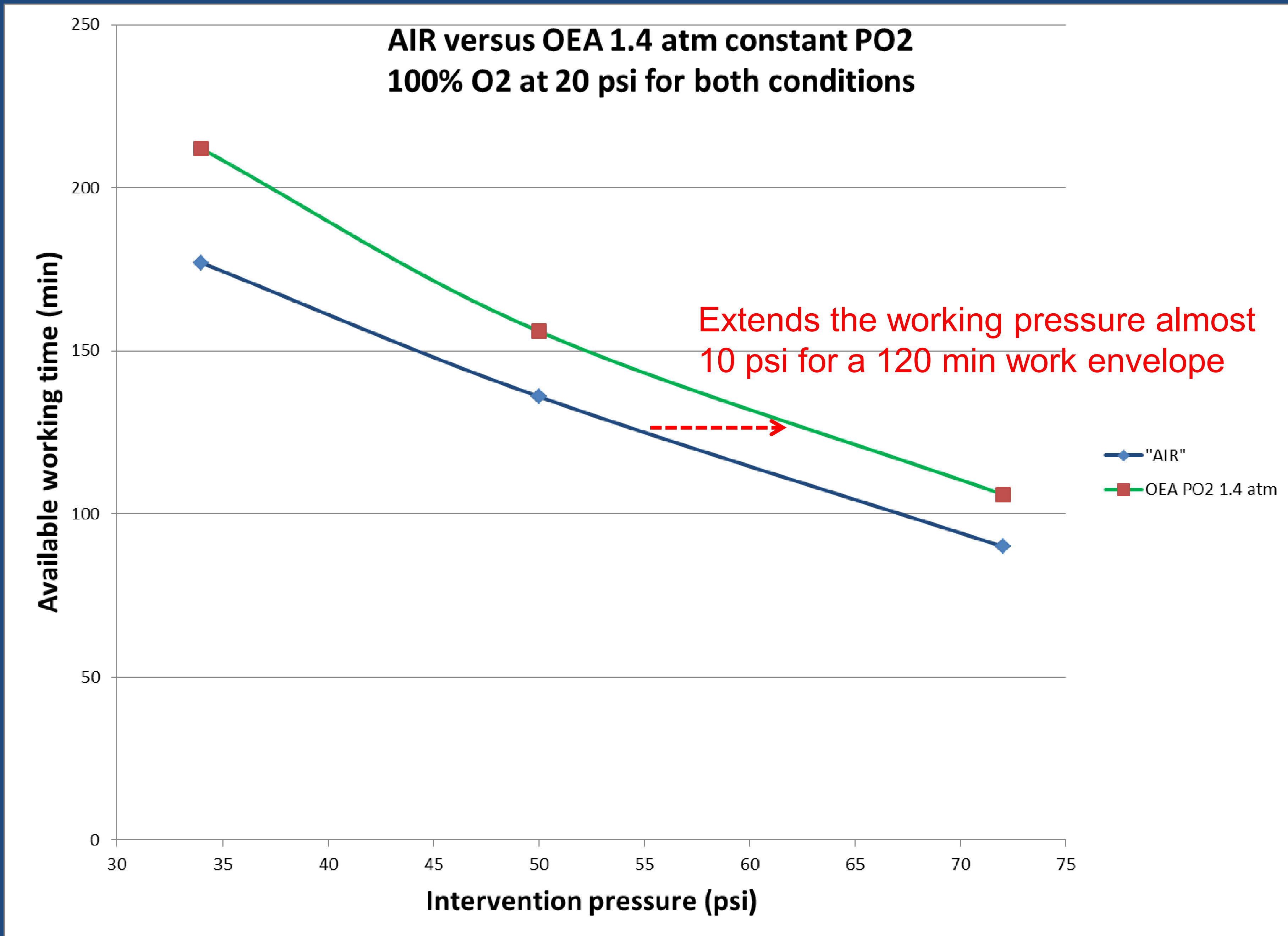
- CO2 removal
- Odor removal
- Other toxic gas removal

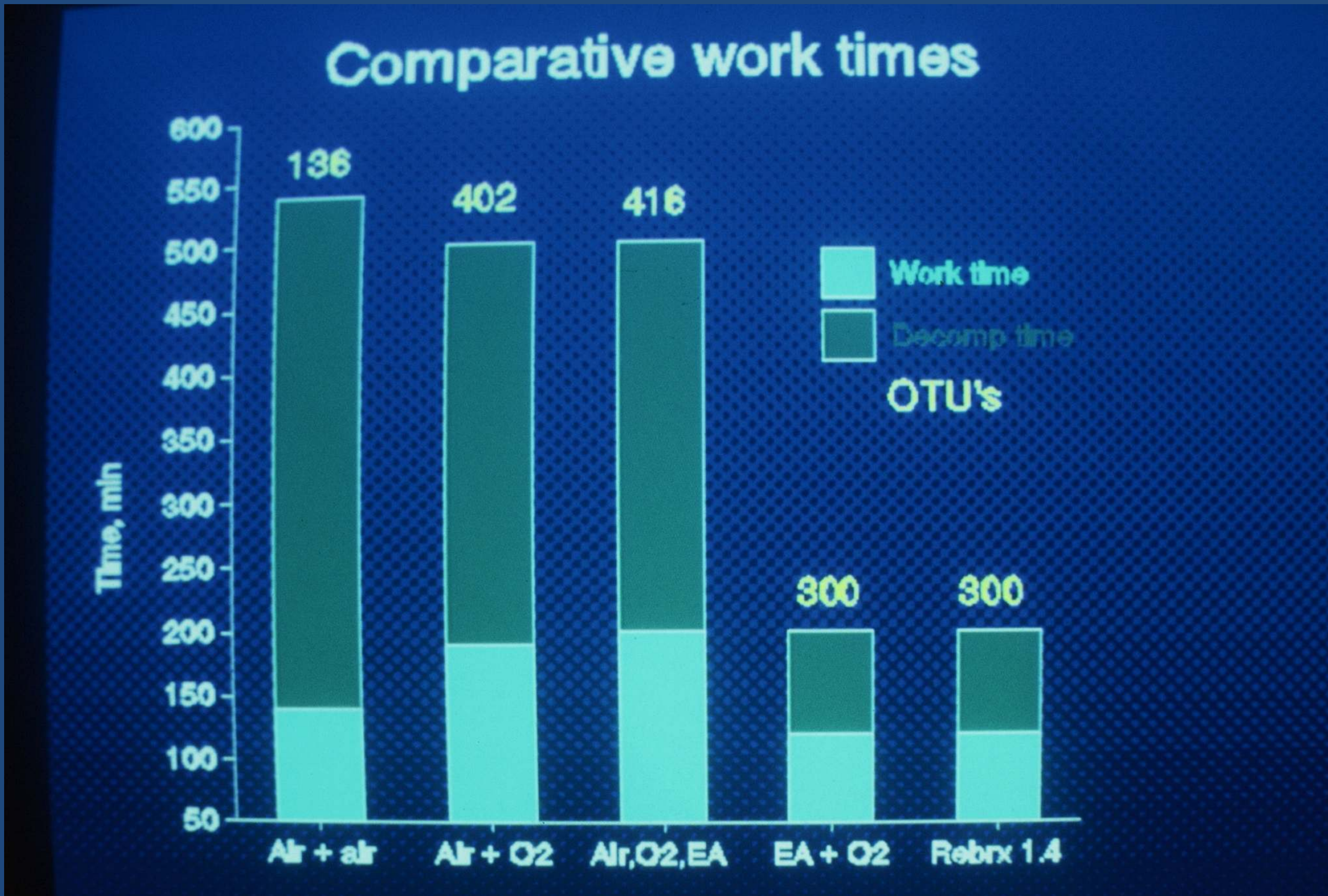
- O2 Addition to maintain an optimal PO2 (under sensor and computer system control)

- Counter lung buffer/compliance

- Diluent gas addition when compressing.

- Automatic exhaust when decompressing

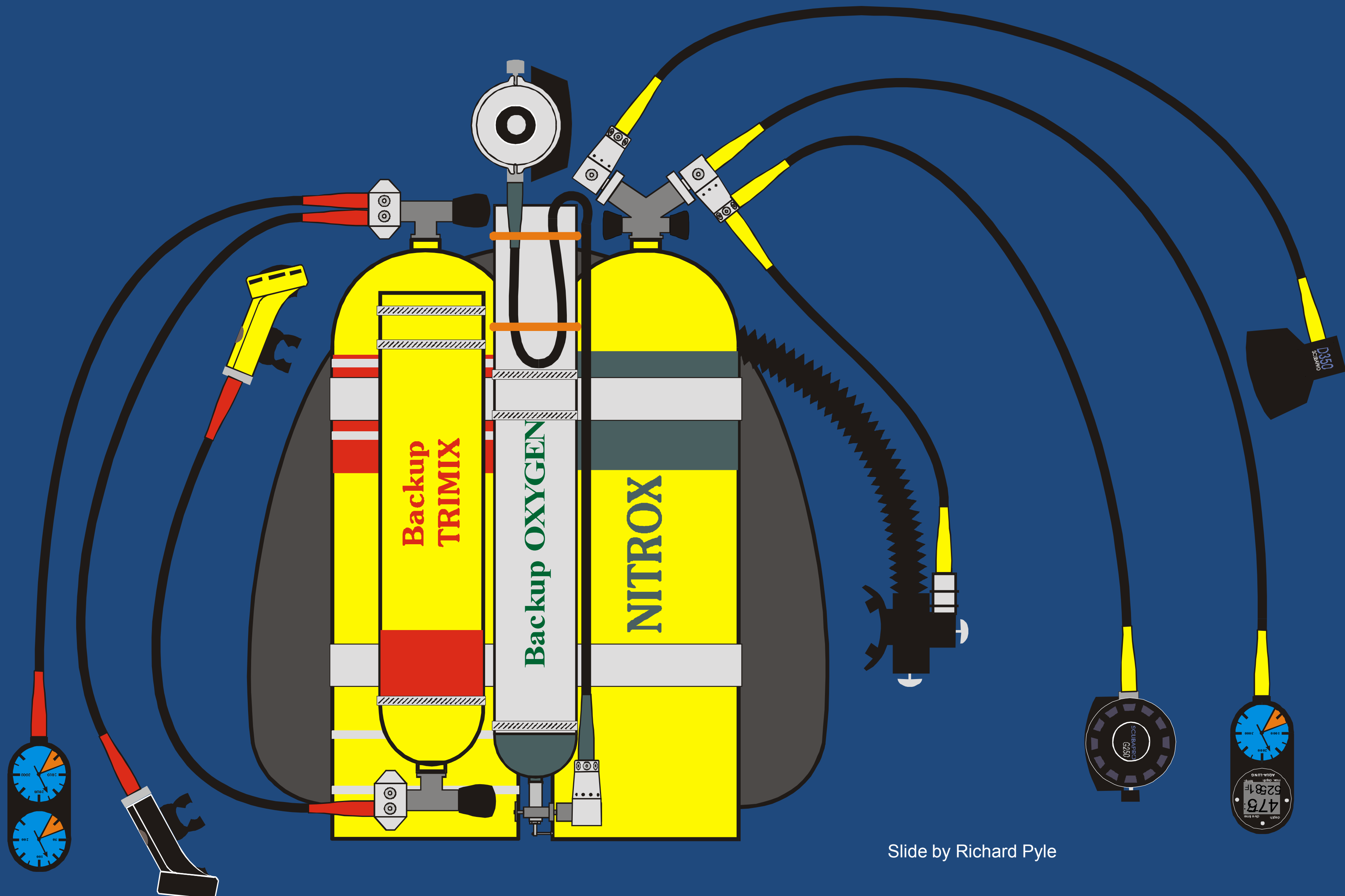

AIR versus OEA 1.4 atm constant PO2
100% O2 at 20 psi for both conditions
Extends the working pressure almost 10 psi for a 120 min work envelope
Available working time (min)
Intervention pressure (psi)
"AIR"
OEA PO2 1.4 atm
0
50
100
150
200
250
30
35
40
45
50
55
60
65
70
75


Comparative work times
Time, min
600
550
500
450
400
350
300
250
200
150
100
50
136
402
416
300
300
Work time
Decomp time
OTU's
Air + air
Air + O2
Air,O2,EA
EA + O2
Rebrx 1.4

Divers learned quickly to use Trimix

- Requirement was to avoid narcosis
  - **Helium** is not narcotic
- An early incentive was cost;
  - Helium is expensive; divers mixed their own so cost of mixing was ignored and parial component of air reduced the costs.
  - Cost any type of Mixed Gas done commercially is expensive
- But trimix **seems** to improve decompression (over helium alone)
- Lots of room to control oxygen

Trimix SCUBA Rig



Slide by Richard Pyle

Use of Trimix (Heliox) for advanced Tunneling Pressures

Dr. Bill Hamilton developed TriMix procedures for a Seattle Outfall tunneling project.

20% O_2, 25% He balance N_2 (55%) followed by 36% Oxygen Enriched Air, then 100% Oxygen; 48 to 88 psi.

- 17% O_2, 30% He balance N_2 (53%) followed by 50% Oxygen Enriched Air, then 100% Oxygen; 50 to 116 psi.

NIOSH draft Trimix Tables
RWH/djk 13Mar29
DtriM1.k00 mp11f6.psi

DEPTH 100 psi
BOTTOM TIME 60 MIN
BOTTOM MIX Trimix
BOTTOM PO2 1.40 atm
Time in minutes

DEPTH psi	STOP TIME	RUN TIME	DEC TIME	MIX	HIPO2 atm	COMMENTS
00	0.0	0.0	0.0	AIR	0.21	BREATHE AIR
100	60.0	60.0	0.0	Trimix	1.40	Breathe Trimix (18% O2, 30 % N2)
100	0.0	60.0	0.0	Trimix	1.40	Ascent rate 10 psi/min
52	3.0	67.8	7.8	Trimix	0.82	Ascent rate 5 psi/min
48	4.0	72.8	12.8	Trimix	0.77	
44	5.0	78.8	18.8	Trimix	0.72	
40	4.0	83.8	23.8	Trimix	0.67	
36	7.0	91.8	31.8	OEA50	1.72	
32	8.0	100.8	40.8	OEA50	1.59	
28	8.0	109.8	49.8	OEA50	1.45	
24	9.0	119.8	59.8	OEA50	1.32	
20	12.0	132.8	72.8	Oxygen	2.36	Breathe O2, rate 1 psi/min
16	13.0	146.8	86.8	Oxygen	2.09	
12	20.0	167.8	107.8	Oxygen	1.82	
08	31.0	199.8	139.8	Oxygen	1.54	up to 5 min air break every 30 min
04	54.0	254.8	194.8	Oxygen	1.27	
00	0.0	255.8	195.8	Oxygen	1.00	Breathe air
						CHAMBER REACHES SURFACE PRESSURE

DCAP allowed O2 Limits

PO2 Time Limits for Working Levels of Oxygen Partial Pressure

PO2 atm	0.5	1.0	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Time min	1440	600	200	120	30	15	10	3	0

Table 7b PO2 Time Limits for Resting Levels of Oxygen Partial Presure

PO2 atm	0.5	1.0	1.4	1.5	1.62	1.7	1.8	1.9	2.0
Time min	1440	600	360	180	60	30	15	6	0

Table 7c PO2 Time Limits for In Chamber Levels of Oxygen Partial Pressure

PO2 atm	0.5	1.0	2.0	2.4	2.6	2.83	2.9	3.0	3.1
Time min	1440	600	120	90	90	90	20	5	0

Surface decompression

- Instead of decompressing in the water to the surface, the diver holds at a depth that is:
  - Not influenced by wave action
  - Suitable for decanting to surface for up to 5 min.
  - Typically 40 fsw.
- The diver goes from 40 fsw to surface, gets out of his gear, enters a deck decompression chamber, and recompresses back to 40 fsw.
- The duration of the decompression is done at 40 fsw while on Oxygen within the DDC

Mobile Re-compression is required

Repex

- Diver/Worker is compressed to a “Habitat”
- Excursions to/from the working pressure involve no decompression or 1 stop decomp. decompression back to the “Habitat” .
- Multiple excursions are allowed/determined.
- Divers/Workers continue to work from the Saturation “habitat” pressure usually at shallow depth/pressure.
- Final Decompression is done from the shallow habitat pressure.

Maximum excursion time allowed at pressure from 20 psi saturation

Habitat Pressure psi	Condition	Excursion Pressure psi	Δ pressure psi	Allowed Work time Minutes (2)	USN Tables Work Time minutes (3)	USN Tables Decomp time minutes(1)
20	No-D	50	26	480	180	110 fsw/ 298
"	No-D	60	36	134	120	130 fsw/ 255
"	1 stop for 6 min.	60	36	180	180	130 fsw/ 417
"	No-D	70	46	52	50	150 fsw/ 87
"	1 stop for 9 min.	70	46	90	90	150 fsw/ 239
"	1 stop for 18 min.	70	46	120	120	150 fsw/ 355
"	1 stop for 38 min.	70	46	187	180	150 fsw/ 537
"	No-D	80	56	20	20	180 fsw/ 26
"	1 stop for 9 min.	80	56	60	60	180 fsw/ 205
"	1 stop for 22 min.	80	56	82	70	180 fsw/ 253

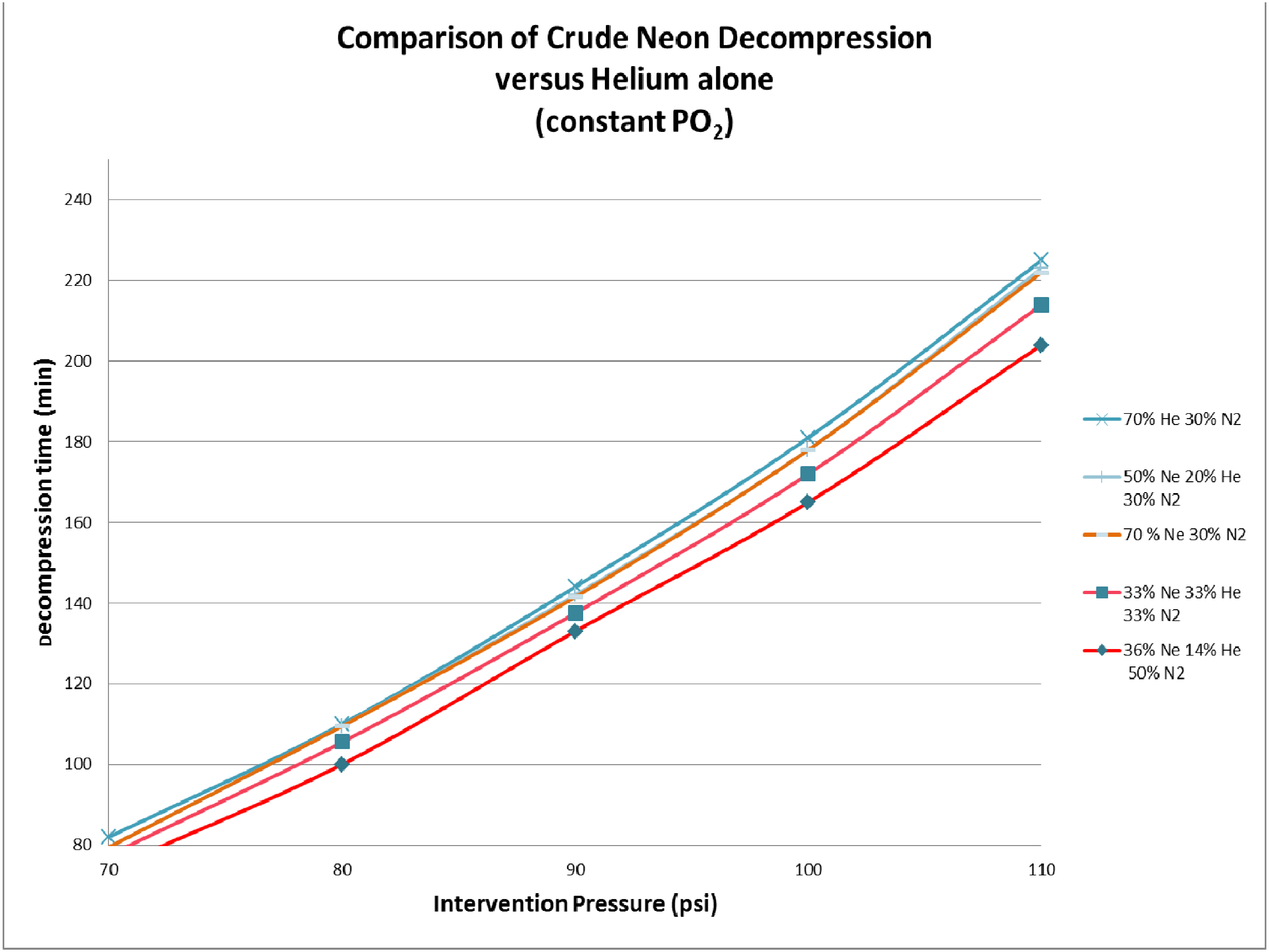
Note 1: Assuming that the worker is decompressing back to 1 atm (0 psi) pressure

Note 2: PO2 1.4 atm at pressure and during decompression

Note 3: Closest Table (fsw/minutes) - USN Diving Manual Table 9-9

Mixed Gases other than Helium

- Hydrogen
- Neon
- Crude Neon



Comparison of Crude Neon Decompression
versus Helium alone
(constant PO_2)
decompression time (min)
240
220
200
180
160
140
120
100
80
70
80
90
100
110
Intervention Pressure (psi)
70% He 30% N2
50% Ne 20% He 30% N2
70 % Ne 30% N2
33% Ne 33% He 33% N2
36% Ne 14% He 50% N2

Specialize Workers and training

- Deeper Tunnels will require longer decompression times.
- Union and some governmental restrictions will limit the time for the classical “compressed air worker”.
- An “A-team” is needed by tunneling contractors that understand the technology and continuously train for the specific task.

In Summary!

- Deep tunnels will require Different techniques
- Tunneling can benefit from other technologies
- The use of more Oxygen will help
  - PO2 of from 1.2 to 1.4 at pressure
  - Higher partial pressures during decompression with OEA “Oxygen Enriched Air”
- The addition of Nitrogen in Deep tunneling
- Specialized equipment, personnel and training

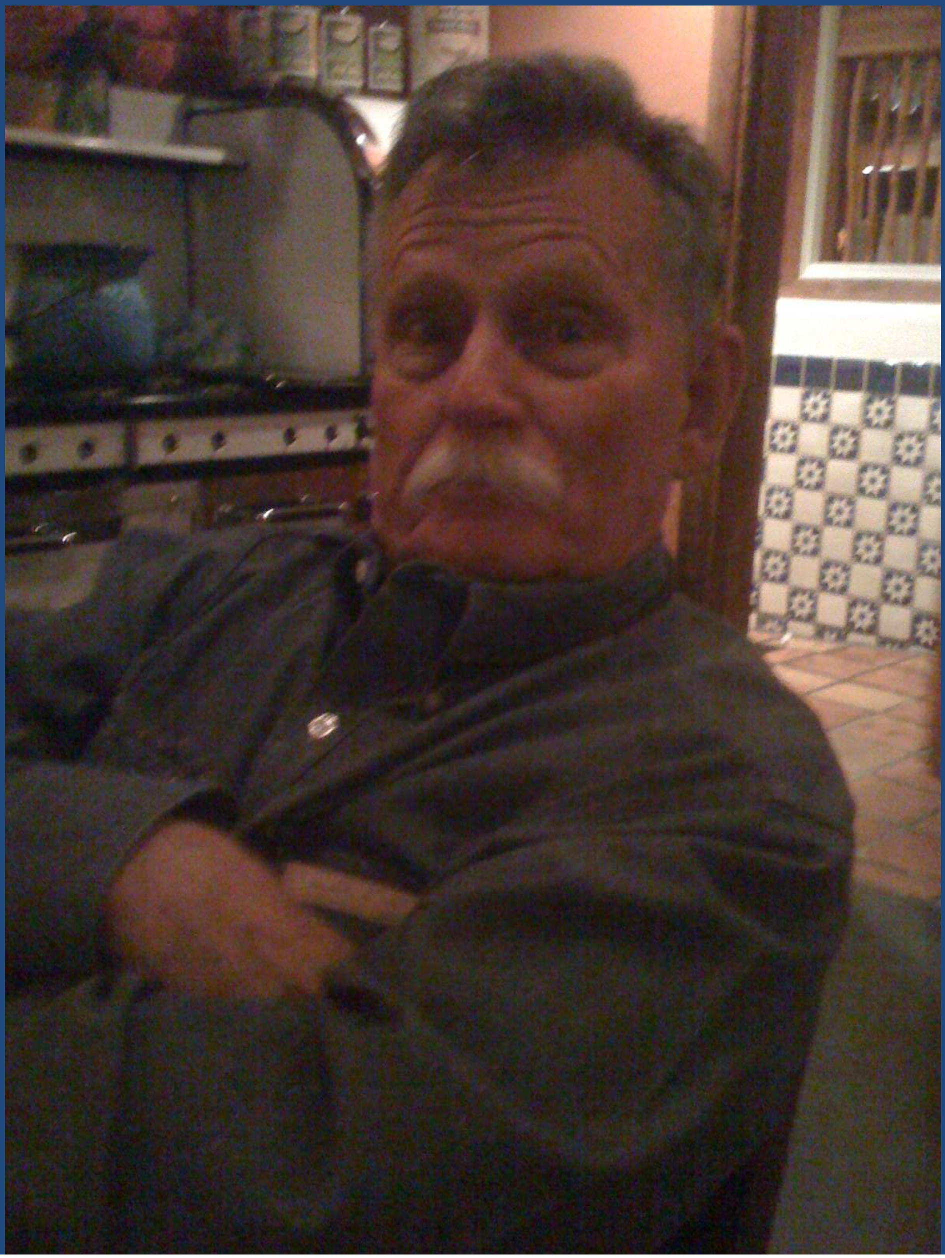
Tunneling

Shallow

- Air only at pressure
  - 21% Oxygen percentage
  - No masks
- Air Decompression and Oxygen by mask
- Compressed air workers
  - “Sand Hogs” - Union
  - “Divers” - >240 min.

Deep

- TriMix and “QuadMix”
  - 1.4 PO2 atm
  - Light weight Open circuit
- OEA and Oxygen
  - PO2 from 1.2 to 1.4 atm
  - Recirculating systems
- Specialized crews
  - A-team selected for job
  - Trained in the use of Mixed Gases and special equipment.



Thanks Bill!

Dave Kenyon
Principal Engineer

Hamilton Research, Ltd.

Thank You!