Submarine Life Support

applied respiratory physiology

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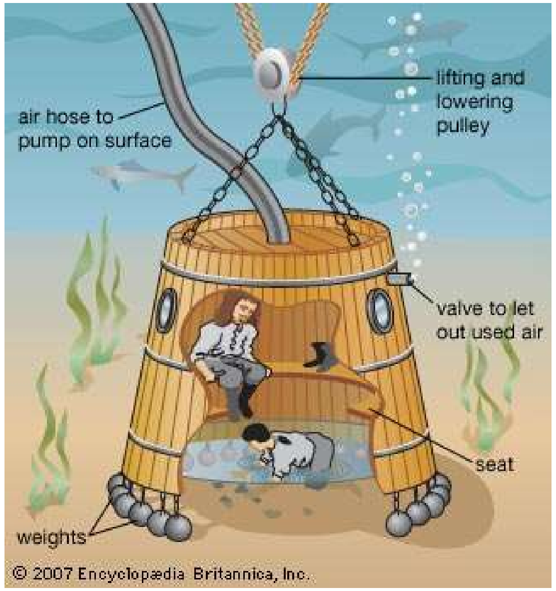
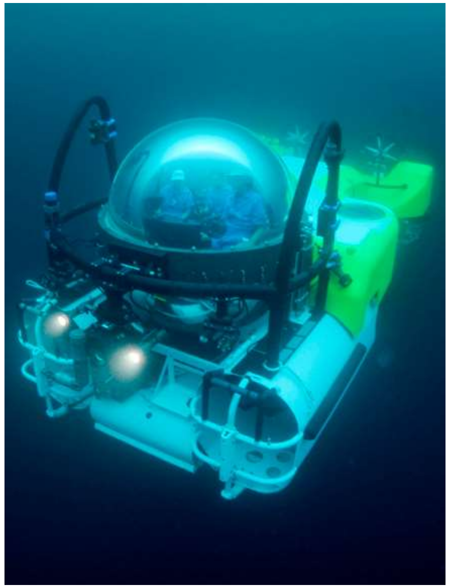
Submariner / Anaesthesiologist-intensivist & DMP

Presented by Jos Bogaert

What is a submarine?

- designed to operate submersed
- contained space with a pressure hull
- atmospheric pressure inside



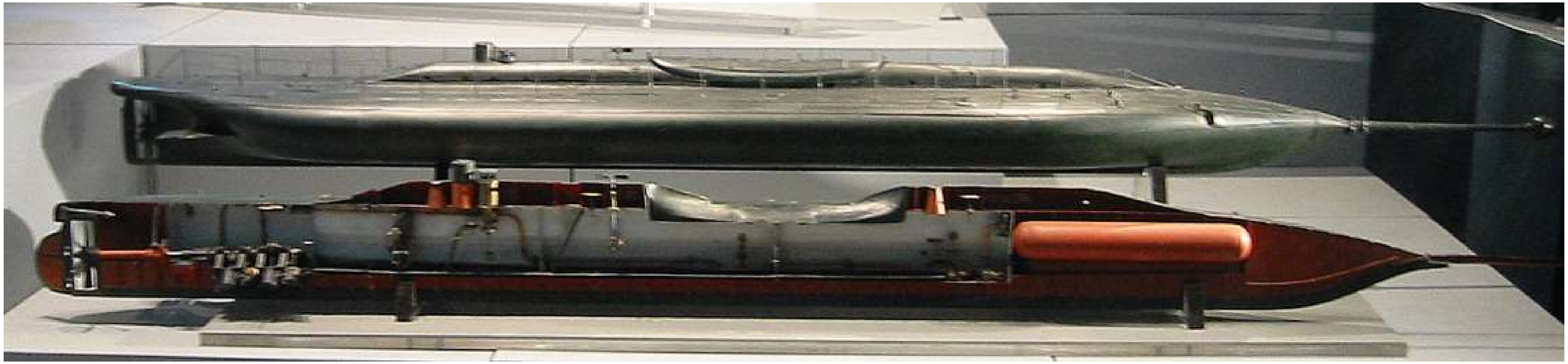


a Dutch invention: the first submarine 1620

The first submersible of whose construction there exists reliable information was built in 1620 by Cornelius Drebbel, a Dutchman in the service of James I of England.

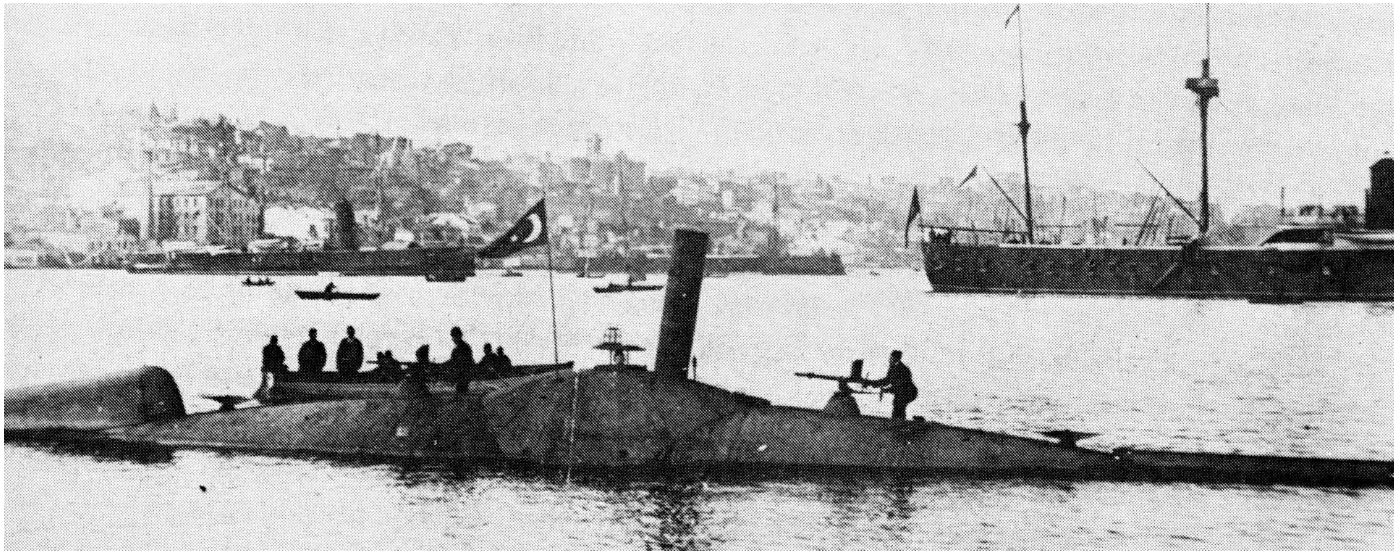
The ***Turtle*** (also called the ***American Turtle***) was the world's first submersible with a documented record of use in combat. It was built in Old Saybrook, Connecticut in 1775 by American Patriot David Bushnell as a means of attaching explosive charges to ships in a harbor.

Compressed air powered propulsion 1863



Plongeur (French for "Diver") was a French submarine launched on 16 April 1863. She was the first submarine in the world to be propelled by mechanical (rather than human) power. The submarine used a compressed-air engine, propelled by stored compressed air powering a reciprocating engine. The air was contained in 23 tanks holding air at 12.5 bar(1.25 MPa, 180 psi), taking up a huge amount of space (153 m^3/5,403 ft^3), and requiring the submarine to be of unprecedented size. The engine had a power of 60 kW (80 hp), and could propel the submarine for 5 nmi (9 km), at a speed of 4 kn (7.2 km/h).

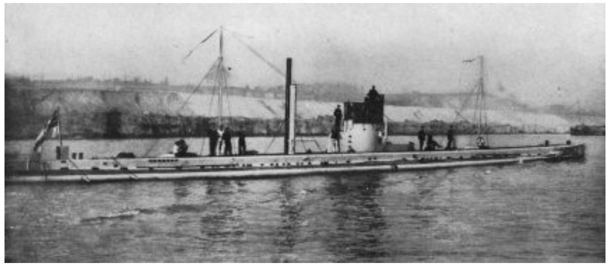
Steam powered propulsion 1885



first practical steam-powered submarines, armed with torpedoes and ready for military use. The first was the *Nordenfelt I*, a 56 tonne, 19.5 meter (64 ft) vessel), with a range of 240 kilometers (150 mi, 130 nm), armed with a single torpedo, in 1885. *Nordenfelt I* operated on the surface by steam, then shut down its engine to dive. While submerged the submarine released pressure generated when the engine was running on the surface to provide propulsion for some distance underwater.

Battery powered propulsion 1878

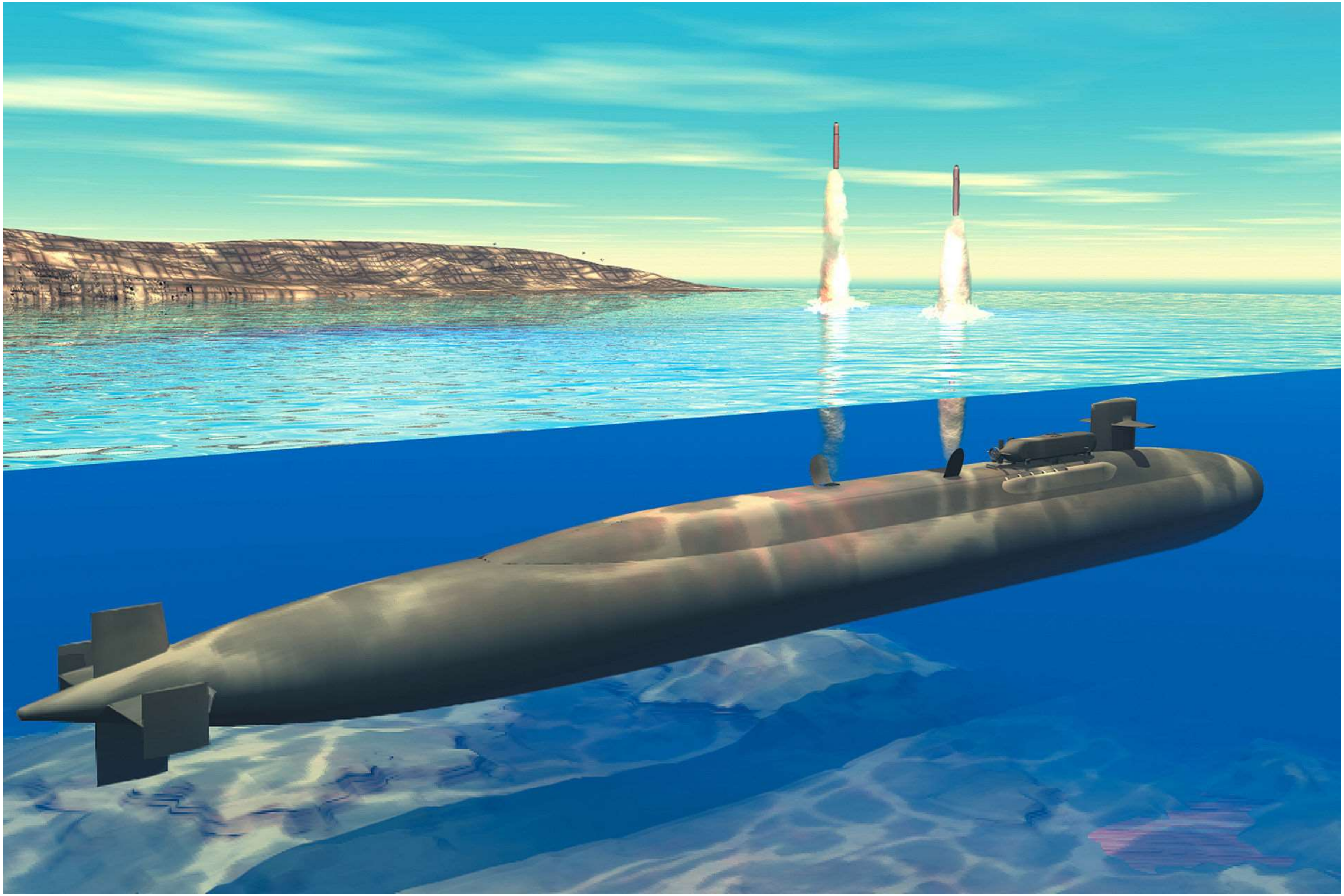
The Irish inventor John Philip Holland built a model submarine in 1876 and a full scale one in 1878, followed by a number of unsuccessful ones. In 1896 he designed the Holland Type VI submarine. This vessel made use of internal combustion engine power on the surface and electric battery power for submerged operations.



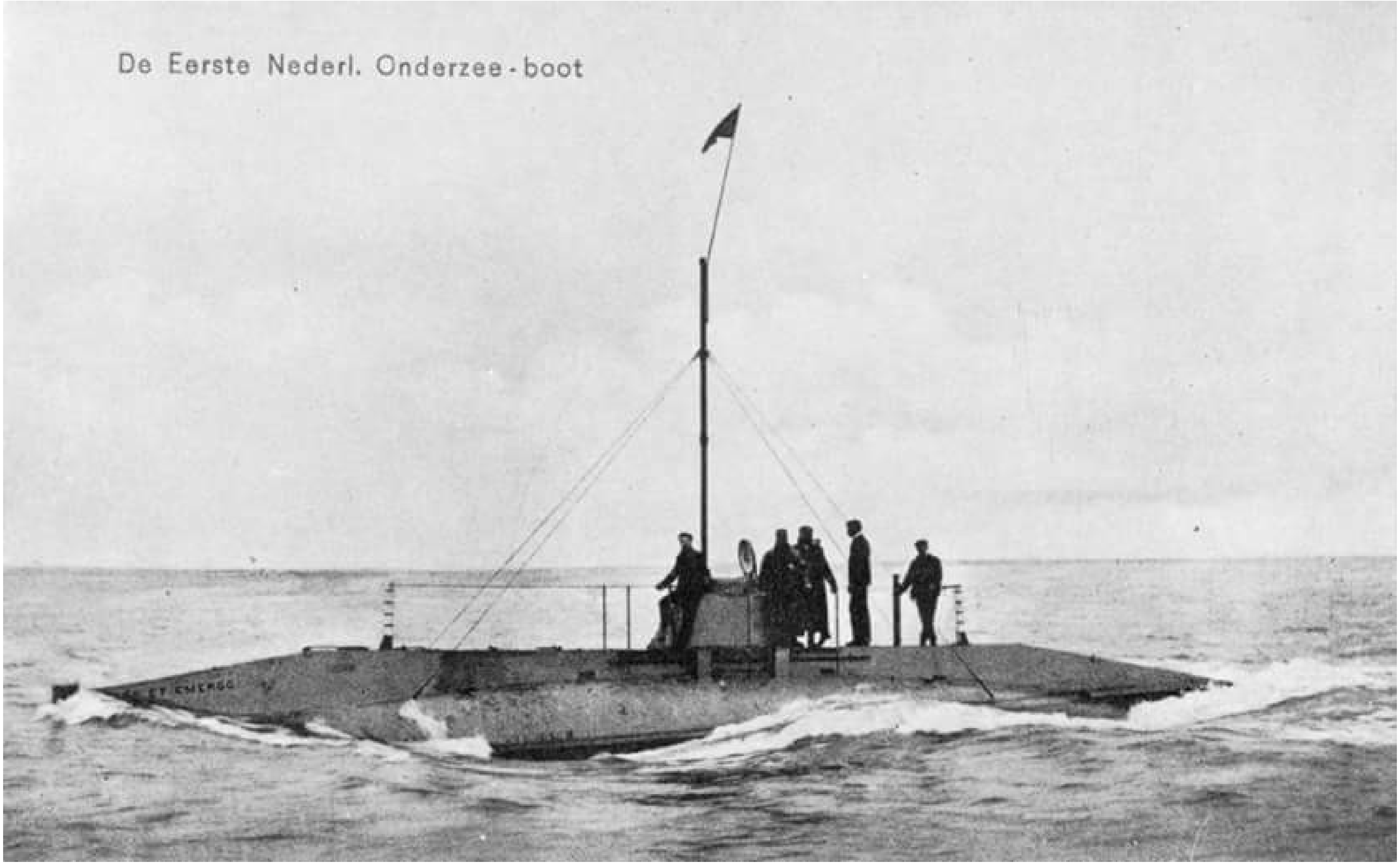
U-9 1910

German submarines at Kiel, Schleswig-Holstein, on 17 February 1914. As U 22 (the newest boat) was commissioned in November 1913, the photo was taken in 1914. Caption says: "Our submarine boats in the harbor" (in German).

Nuclear powered submarine Ohio class



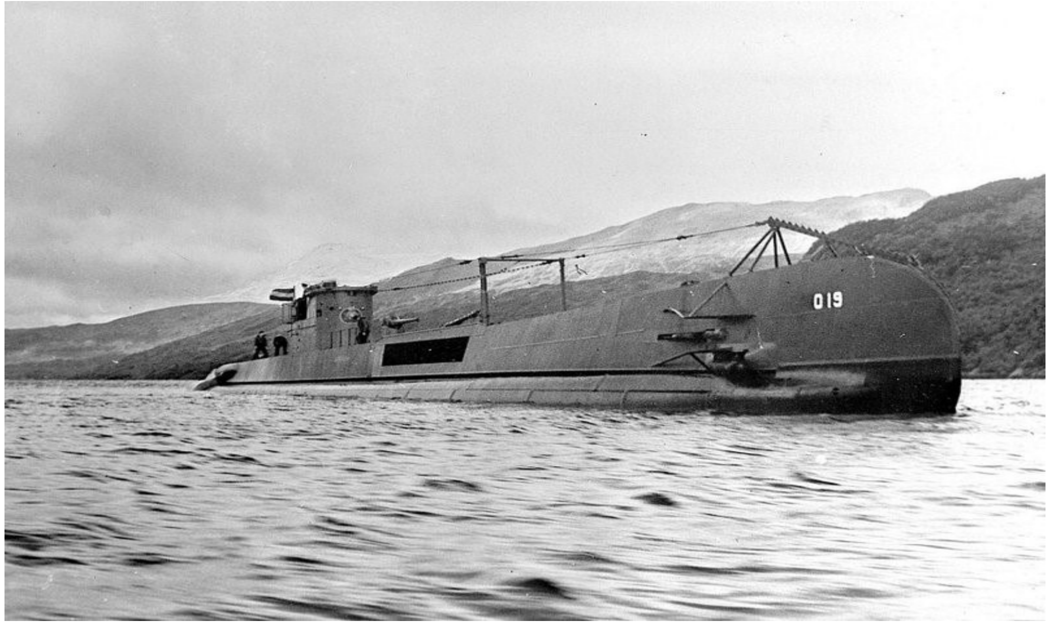
The first Dutch Submarine



Dutch Submarine Service

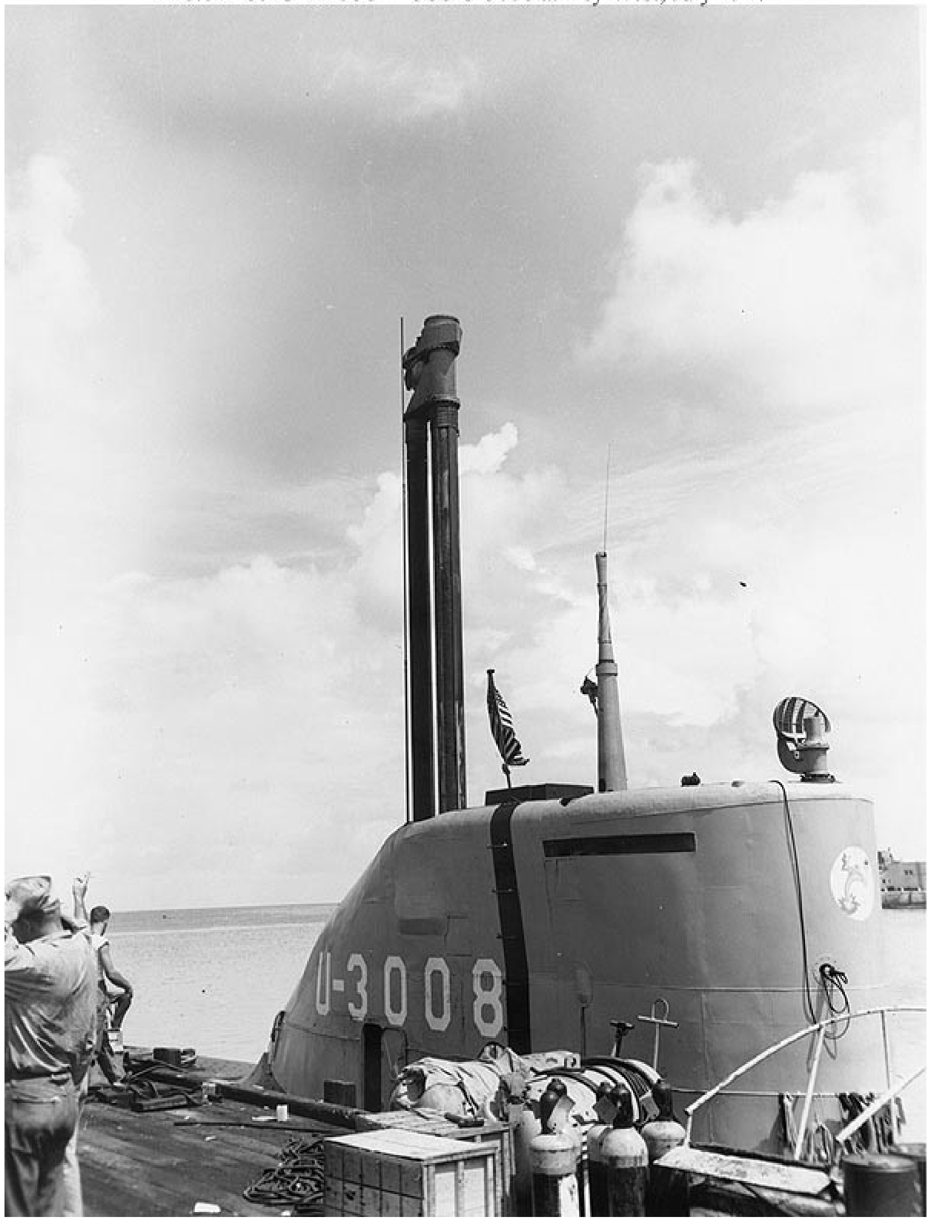
- **Early history**
- The Royal Netherlands Navy Submarine Service (OZD) was established on 21 December 1906. In this year the Royal Netherlands Navy commissioned its first submarine, HNLMS *O 1*. The OZD was tasked with taking care of the equipment of the submarines and the training of the crews.
- At this time there were still doubts about the usefulness of submarines. Royal Netherlands Navy officers did indeed see an "interesting and ingeniously constructed mechanism in the vessel, but were hesitant about their practicality. Trial sailing slowly but surely removed the doubts in the naval command. Only under the influence of the First World War did the officers get more interested in the new type of war material
- **World War II**
- During World War I and the interwar period, the Royal Netherlands Navy ordered and built many submarines. As a result, at the start of World War II, the OZD had more than 20 submarines at its disposal

The snorcle: a Dutch invention!



The Dutch *O-21 series* was operating a device named a *snuiver* (*sniffer*). The Dutch navy had been experimenting as early as 1938 with a simple pipe system on the submarines *O-19* and *O-20* that enabled them to travel at periscope depth operating on its diesels with almost unlimited underwater range while charging the propulsion batteries. The system was designed by the Dutchman Jan Jacob Wichers.

Photo # 80-G-442938   USS U-3008 at Key West, July 1947



Expansion

- After 1945, the OZD had eight submarines, but due to intensive use in the war these were in a bad condition. Also the fact that the fleet consisted of different classes was a problem. It made maintenance and exercise of crews very pricey. Due to the economic malaise and the high costs caused by operations in the Dutch East Indies, there was no money left for new construction. In the end the navy managed to take four submarines on loan from the British and the Americans. In 1946, the Netherlands still had a total of eight operational submarines in service: HNLMS *O 21*, *O 23*, *O 24*, *O 27*, *Dolfijn*, *Zwaardvisch*, *Zeehond*, and *Tijgerhaai*.

- For the OZD, this period just after World War II meant depending on Dutch pre-war submarines and second-hand British and American submarines. The commissioning of the *Dolfijn*-class submarines in the early 1960s was an important milestone. The four boats formed the backbone of the OZD during a large part of the Cold War; they were in service from 1960 to 1992
- **Cold War**
- The Dutch submarine fleet never reached the size it had before the World War II again The new global power relations also generated a new package of tasks. In cooperation with other NATO countries, these are mainly non-attack tasks. Since the Dutch submarines were ideally suited for unnoticed explorations, the OZD was mostly focused on gathering intelligence during the Cold War. This happened, for example, during the West New Guinea dispute in the early 1960s, when three Dutch submarines patroled the Indonesian ports, to warn against possible invasions of West New Guinea

Cold War Missions

- In the period from 1970 to the 1990s, the crew of the six Dutch submarines secretly gathered information about the Soviet Union. Most of the missions the OZD carried out remain secret to this day.
- Although the cold war was not a real war, but there were certain dangers of operating in hostile waters
- During this period there was not much attention for survivability or escape.
- Basic life gasses were monitored but the standards for Co2 were high as the limit for O 2 was verry low.

Research for Survivability

- It was only after the Kursk accident and the fire on board Chicoutimi that RNLN started investigating in 7 days survivability and modern ways of escape and rescue.
- It was only in 2006 that RNLN did their first survivex who was briefed at SAMAP in 2007
- Because Mattijn is working as an Anaesthesiologist he looked at figures of air consumption and CO2 production differently and he took more factors in consideration
- In the following slides the calculations for dissub survival

Submarine Design Challenges

Life support

- temperature
- moisture control
- odours & toxic vapours
- water supply
- oxygen
- carbon dioxide
- submarine escape

Engineering

- streamlining
- pressure hull
- propulsion system (surface and submersed
- navigation
- stealth
- weapon systems
- storage/ interior design

Breathing in an enclosed space

DISSUB: disabled or distressed submarine that is not able to surface and to ventilate it's atmosphere

breathing in an enclosed space
life support system out of order!
calculating endurance.....
"how long before the crew is out of breath?"

Breathing in an enclosed space

What do we need to know?

info needed
Cubic meters
Nr of crew
O_2 consumption rate
CO_2 production rate
Hypoxic tolerance level
Hypercapnic tolerance level

Breathing in an enclosed space

What more do we need to know?

info needed	Additional info
Cubic meters	Submarine model/type
Nr of crew	
O_2 consumption rate	Activity level: ? RQ: ?
CO_2 production rate	
Hypoxic tolerance level	Acceptable degree of incapacitation ? Physical fitness ?
Hypercapnic tolerance level	

Breathing in an enclosed space

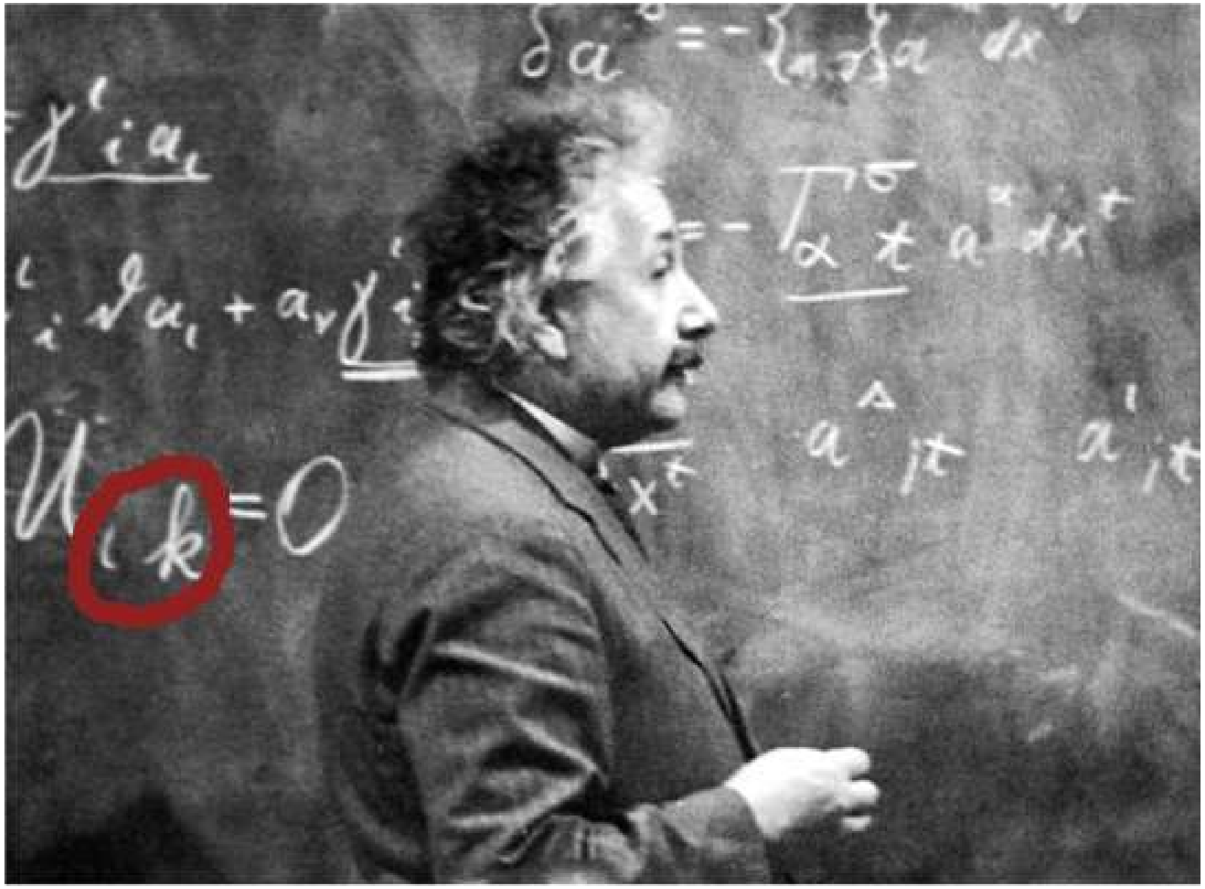
What more do we need to know?

info needed	Additional info	Additional info
Cubic meters	Submarine model/type	Walrus class
Nr of crew		50
O_2 consumption rate	Activity level: ? RQ: ?	diet
CO_2 production rate		
Hypoxic tolerance level	Acceptable degree of incapacitation ? Physical fitness ?	Hypoxic signs & symptoms ? Hypercapnic signs & symptoms ?
Hypercapnic tolerance level		

How long do they have? Before emergency escape or death?

4 groups, use your laptop or Ipad

Let’s try to solve the puzzle together!



The Walrus class

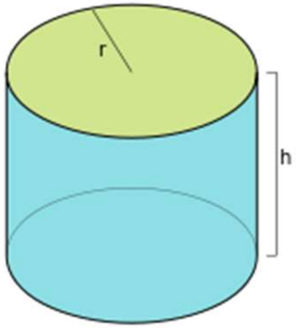
Ship	Laid down	Launched	Commissioned	Fate
Walrus	11 October 1979	28 October 1985	1992	Decommisioned
Zeeleeuw	24 September 1981	20 June 1987	1990	In service
Dolfijn	12 June 1986	25 April 1990	1993	In service
Bruinvis	14 April 1988	25 April/May 1992	1994	In service

General characteristics
Displacement: 2,350 t surfaced, 2,650 t submerged, 1,900 t standard
Dimensions: 67.73 x 8.4 x 6.6 m
Propulsion: 3 SEMT Pielstick 12PA4V200SM diesels, 1 Holec mainmotor, 1 shaft, 6 blades
Speed: 13 knots surfaced, 20 knots submerged
Torpedo tubes:4 torpedos: 20
Crew: 50

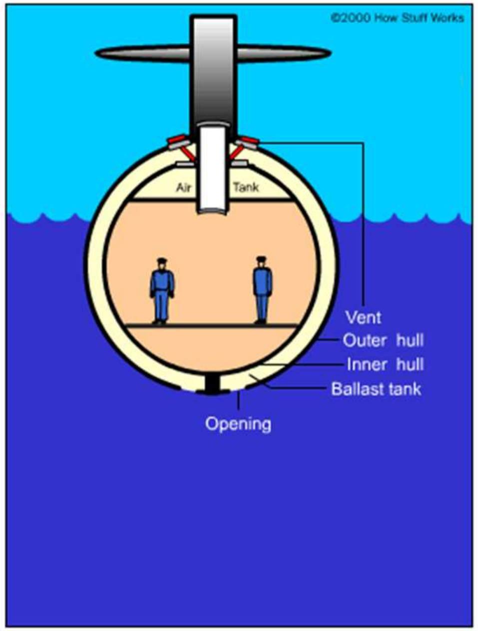
Content inner hull compartment

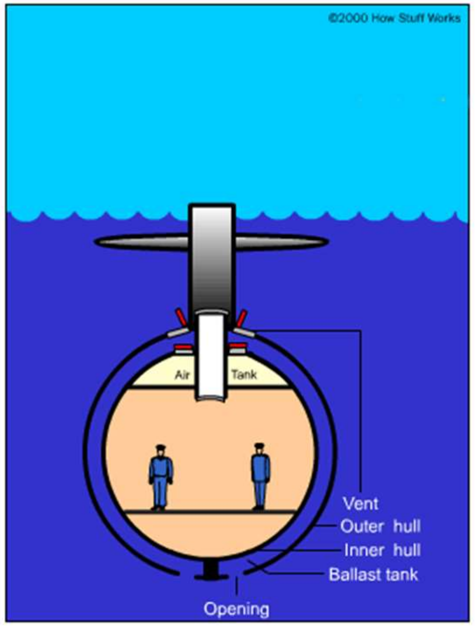
outer dimensions: 67.73 x 8.4 x 6.6

content cylinder : $\prod r^2h$

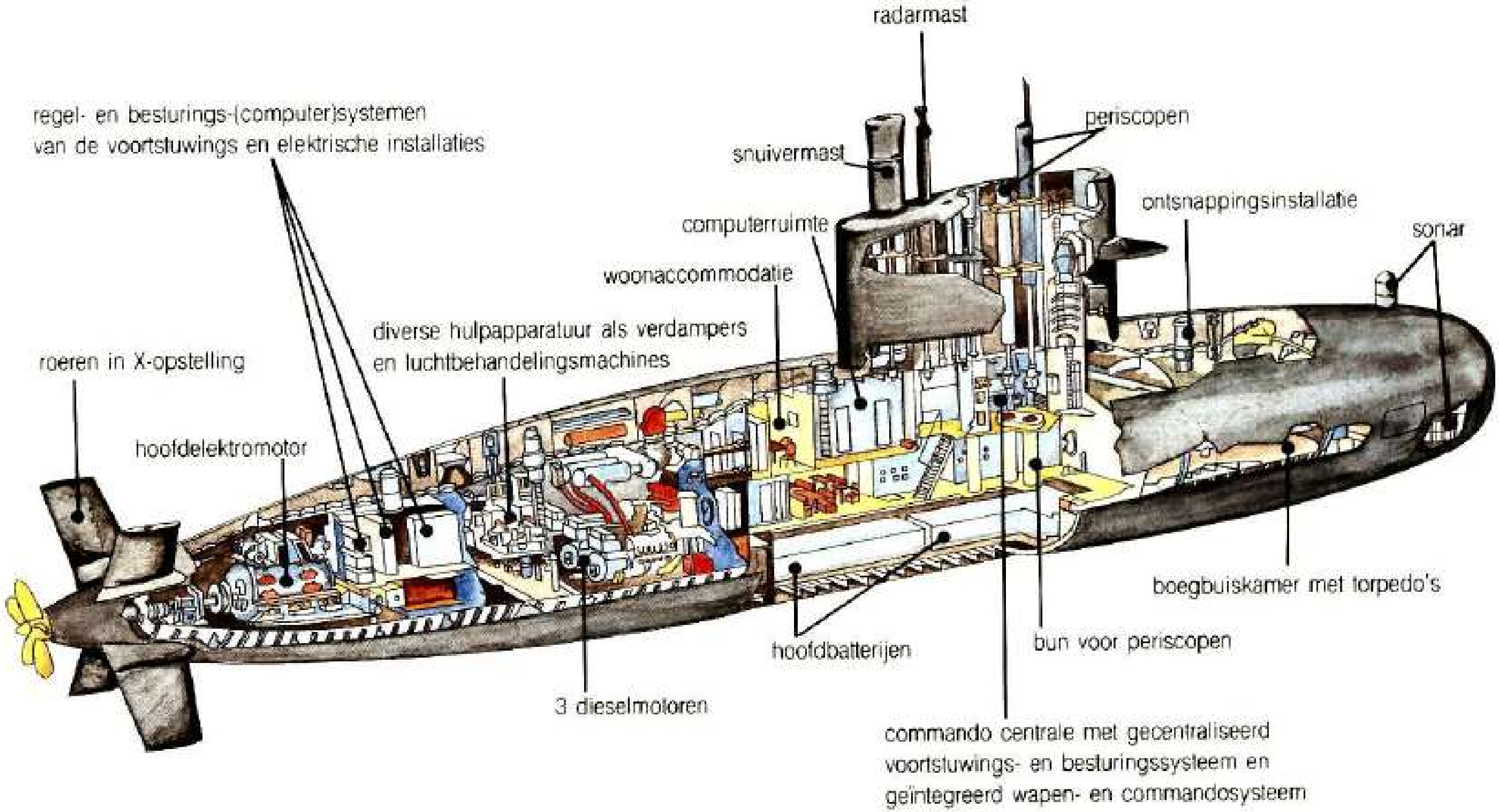


? Cylinder shape
? Constant cylinder

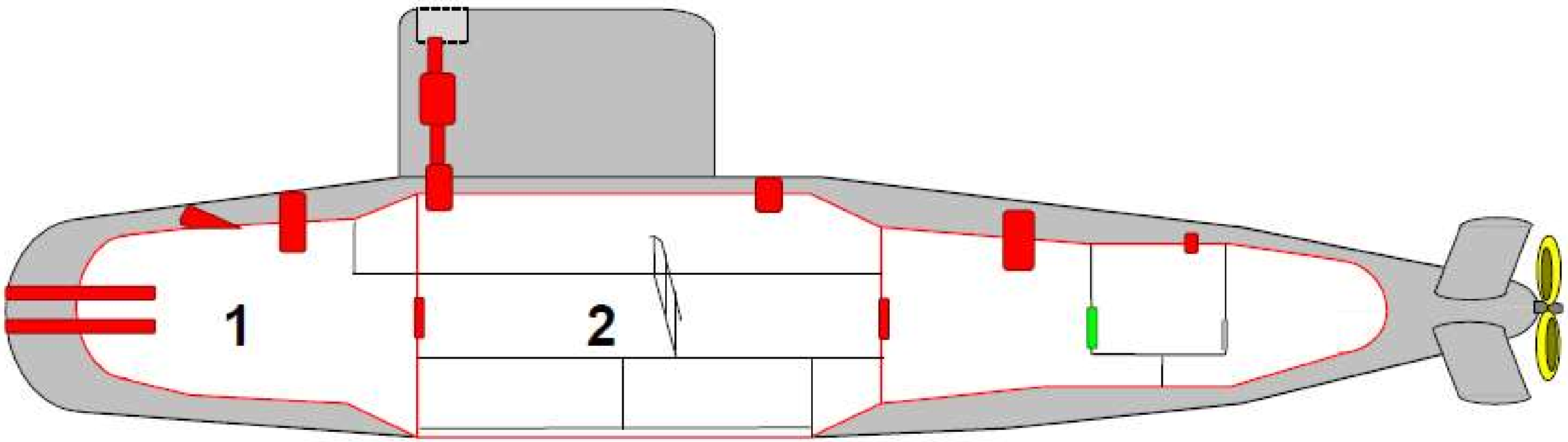




A cramped space indeed!



Official Dutch Navy intell

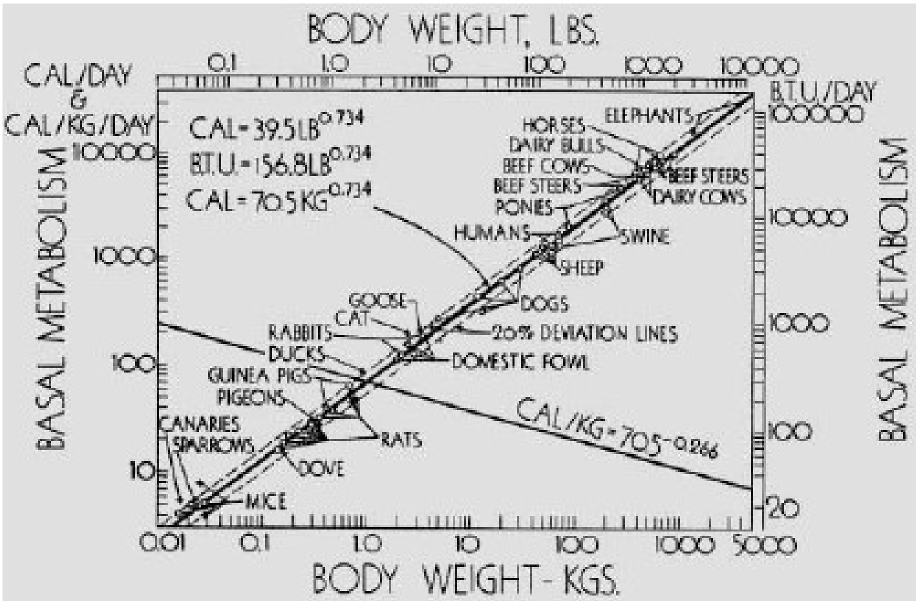


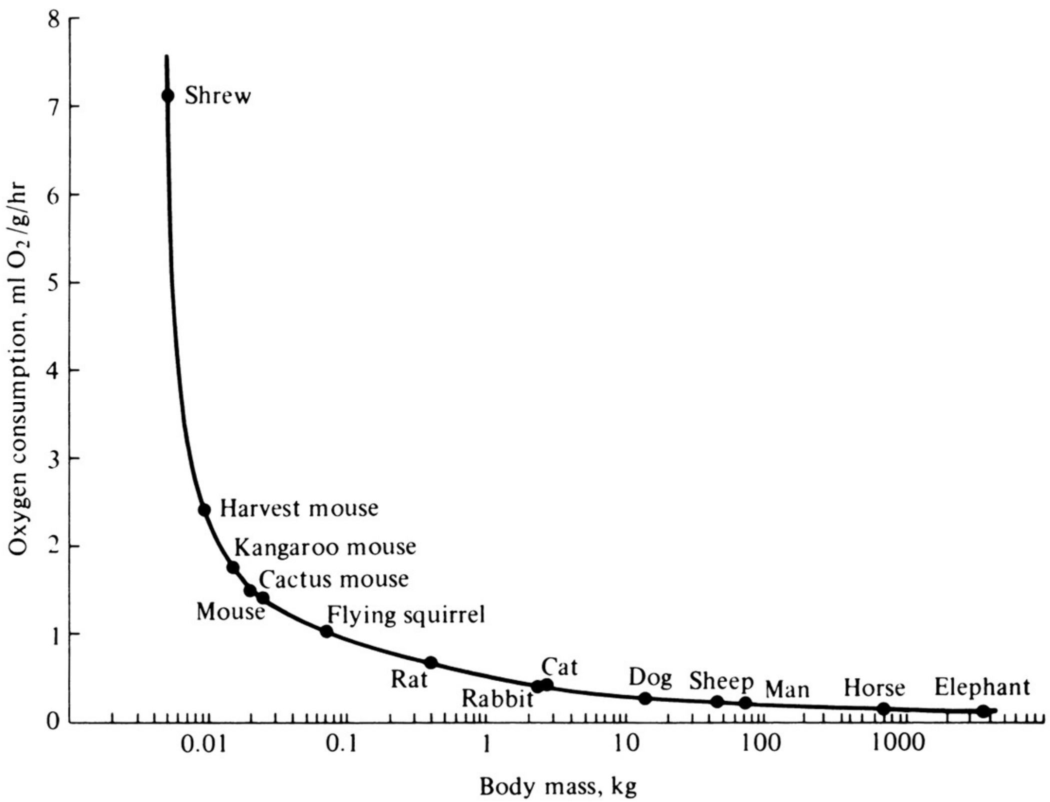
	Bruto	Netto
Volume Aft (MMR, SR & ER)	550	435
Volume Controlroom / accommodation	610	495
Volume Battery Hold	?	70
Volume Forward Escape Compartment	245	200

1200 M^3

Oxygen consumption

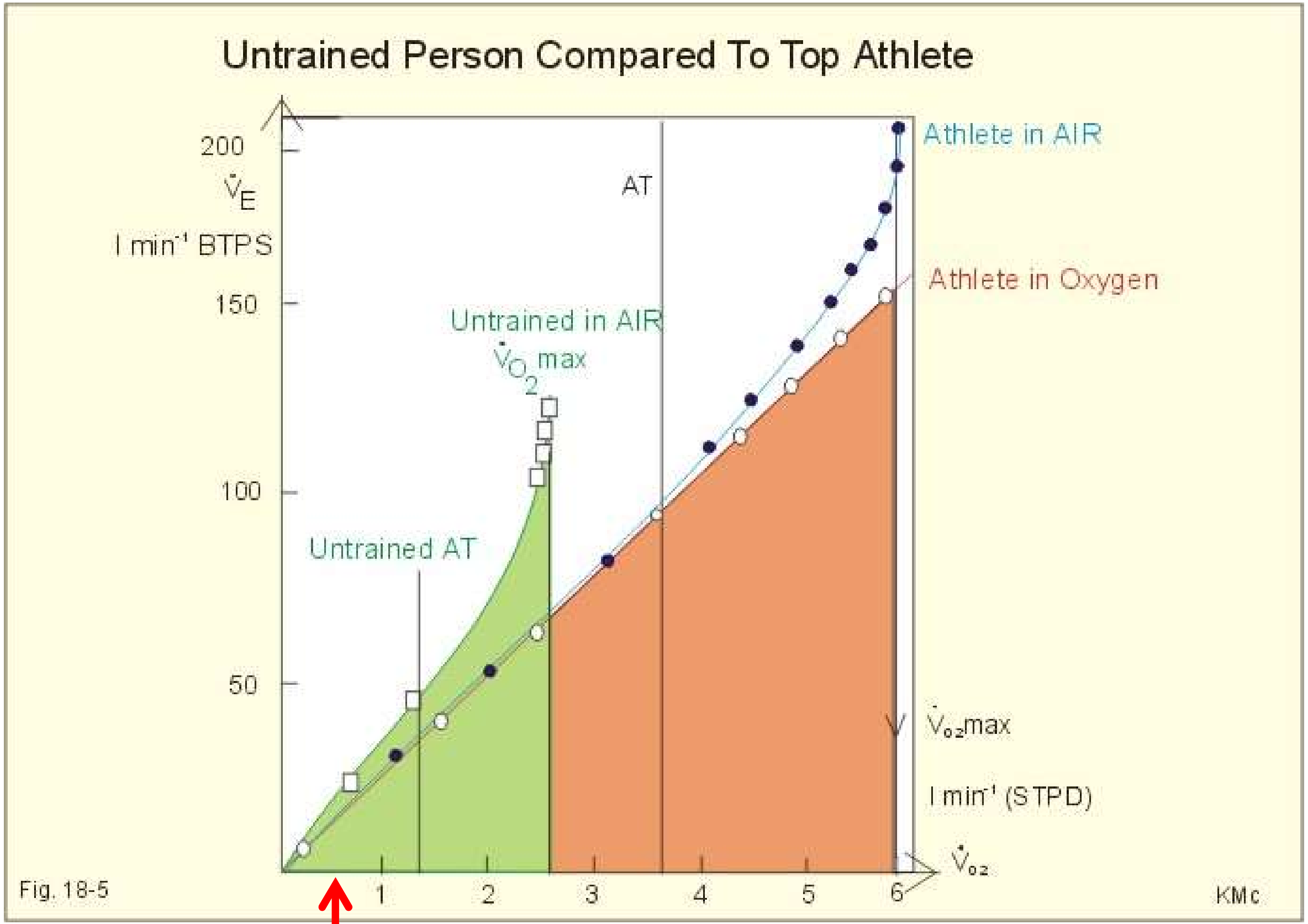
- BMR: 250 ml/min (70 kg)
- DISSUB: inactive crew: ? 400ml/min
- Entraped 440 ml/min (mining industry, 24h average including sleeping):
- Walking: 1 L/min
- Running (12km/h): 3 L/min
- $VO_{2\ max}$ athletes: 6 L/min





Porter RK. Allometry of mammalian cellular oxygen consumption. CMLS 2001;58:815-822

Influence of physical fitness



VO_2 400 ml/min

physical fitness:
increased VO_2 max
decreased VO_2 bas

little training effect
@low VO_2

Most sailors are fit....

RQ

Results: RQ

The RQ is the ratio between the CO_2 produced and O_2 consumed

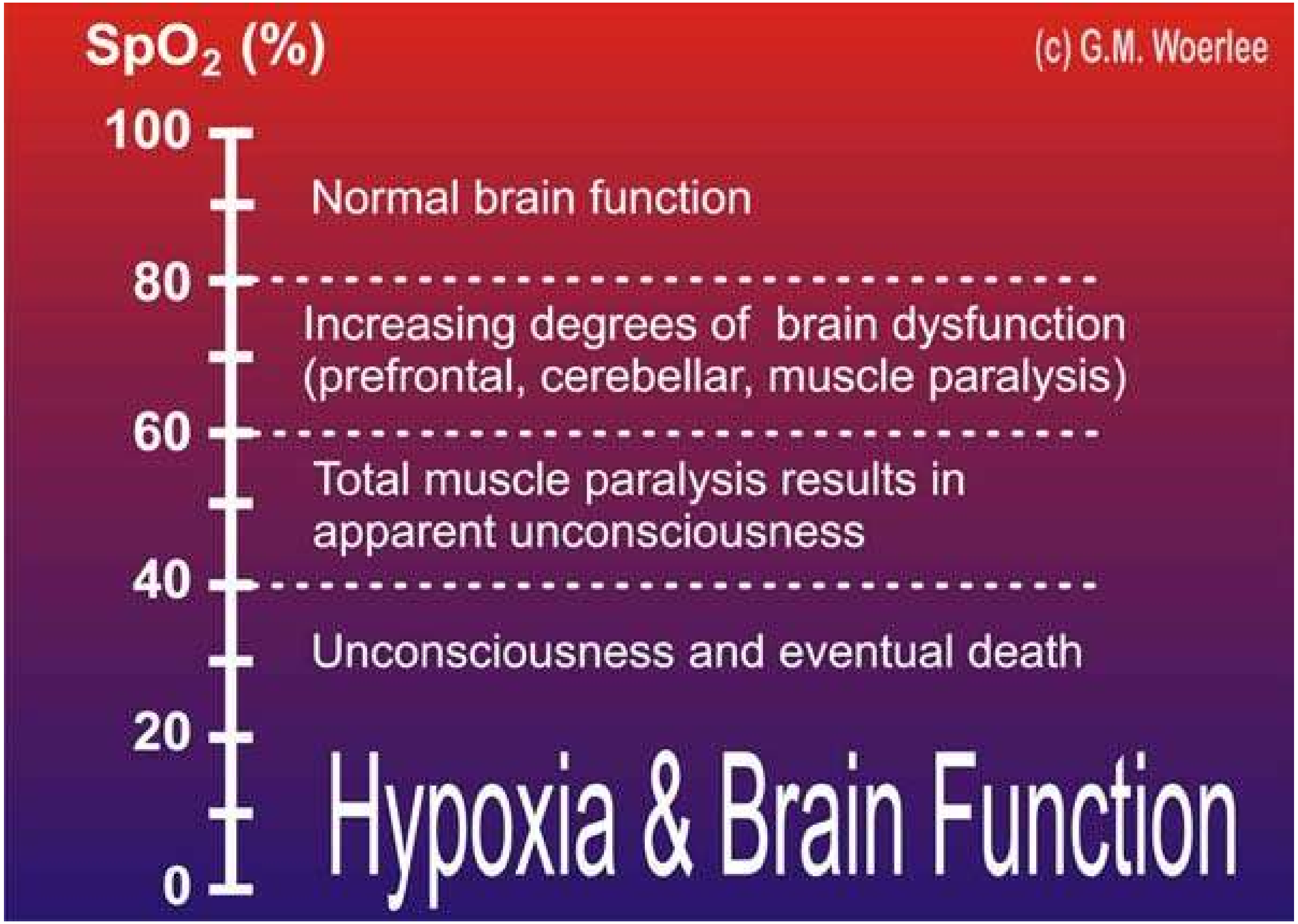
CARB = $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$

FAT = $C_{16}H_{32}O_2 + 23O_2 \rightarrow 16CO_2 + 16H_2O$

RQ	CARB%	FAT %
0.70	0	100
0.75	15.6	84.4
0.80	33.4	66.6
0.85	50.7	49.3
0.90	67.5	32.5
0.95	84.0	16.0
1.00	100	0

More carbs > more CO_2 produced
Average diet RQ = 0.8

Hypoxia & the brain



What is the reliability of SpO_2 in the lower range?

Reliability of SpO_2

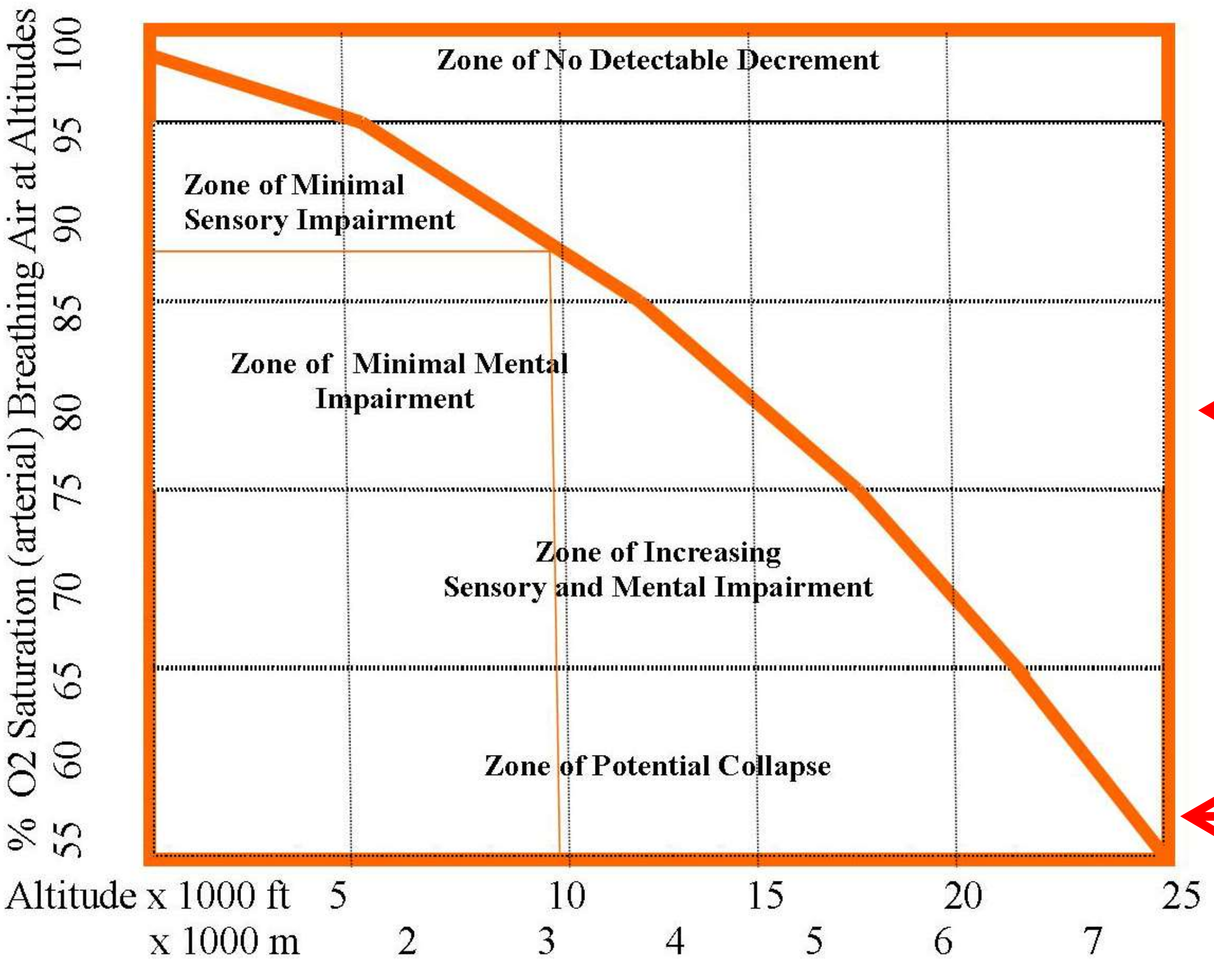
- 100 – 70% range   accuracy 2-4%
- < 70% ?
- pulsoximetry is calibrated in the 70-100% range with healthy volunteers.
- In the lower range it is the 660 nm led alone that measures absorption. Any variation in 660 nm LED output will have a large influence on accuracy

Milner QJW, Mathews GR. An assessment of the accuracy of pulse oximeters. Anaesthesia 2012, 67, 396–401

VO_2 and CO_2 production

info needed	Additional info	Additional info
Cubic meters	Submarine model/type	Walrus class = 1200 M^3
Nr of crew		50
O_2 consumption rate	Activity level: surveillance mode VO_2 = 400 ml/min CO_2 = 320 ml/min	RQ = 0.8 Standard diet
CO_2 production rate		
Hypoxic tolerance level	Acceptable degree of incapacitation Physical fitness	Hypoxic signs & symptoms Hypercapnic signs & symptoms
Hypercapnic tolerance level		

How low can you go?



No longer able to function under operational conditions

Risk of death

Hypoxia & aviation

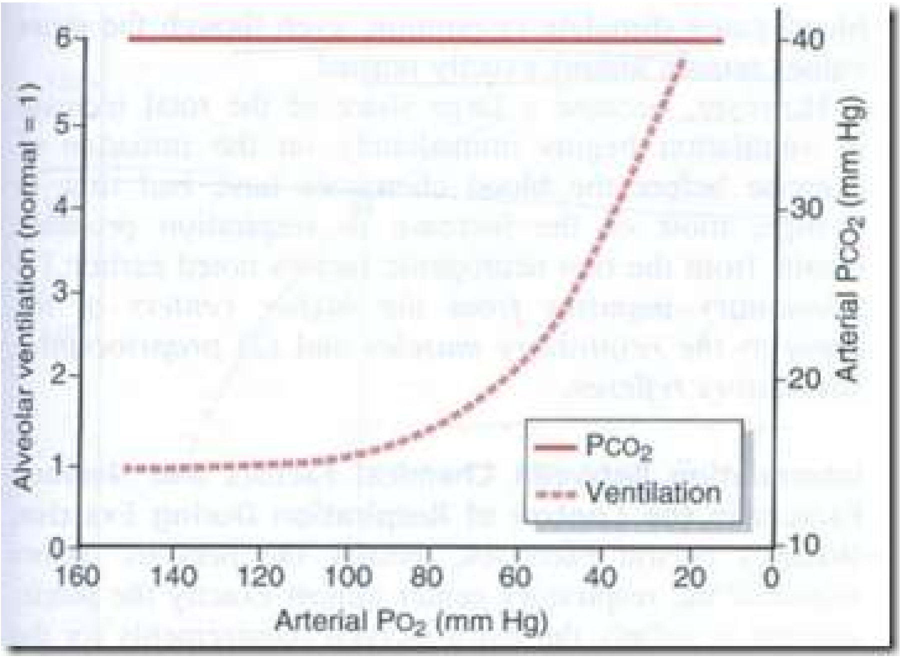
Stages	Indifferent Stage (98%–90% O_2 saturation)	Compensatory Stage (89%–80% O_2 saturation)	Disturbance Stage (79%–70% O_2 saturation)	Critical Stage (69%–60% O_2 saturation)
Altitude (thousands of feet)	0–10	10–15	15–20	20–25
Symptoms	Decrease in night vision	Drowsiness Poor judgment Impaired coordination Impaired efficiency	Impaired flight control Impaired handwriting Impaired speech Decreased coordination Impaired vision Decreased sensation to pain Impaired intellectual function Decreased memory Impaired judgment	Circulatory failure CNS failure Convulsions Cardiovascular collapse Death

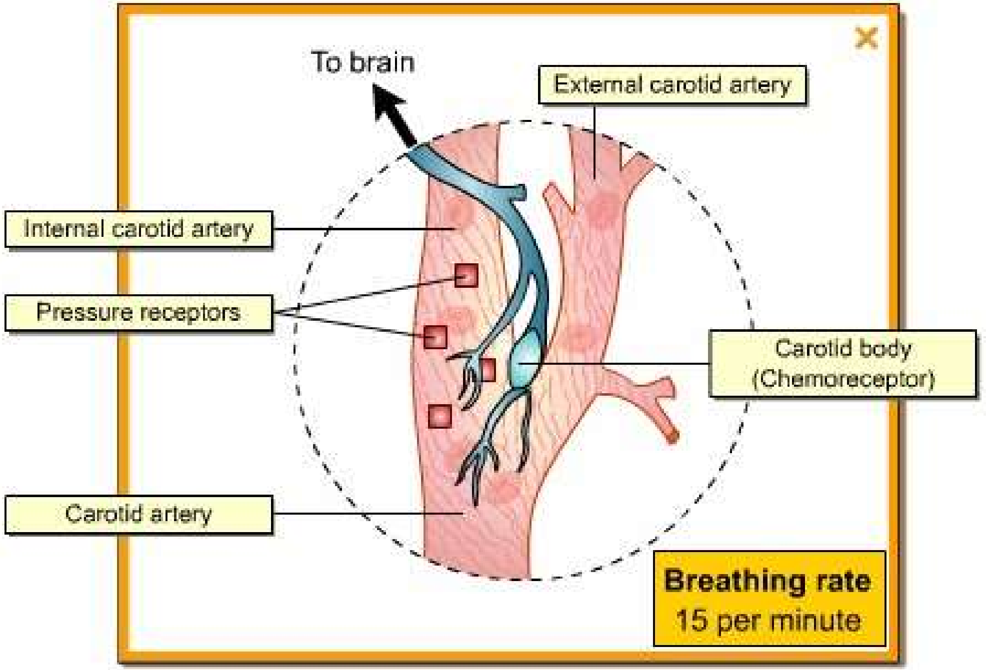
Mining industry

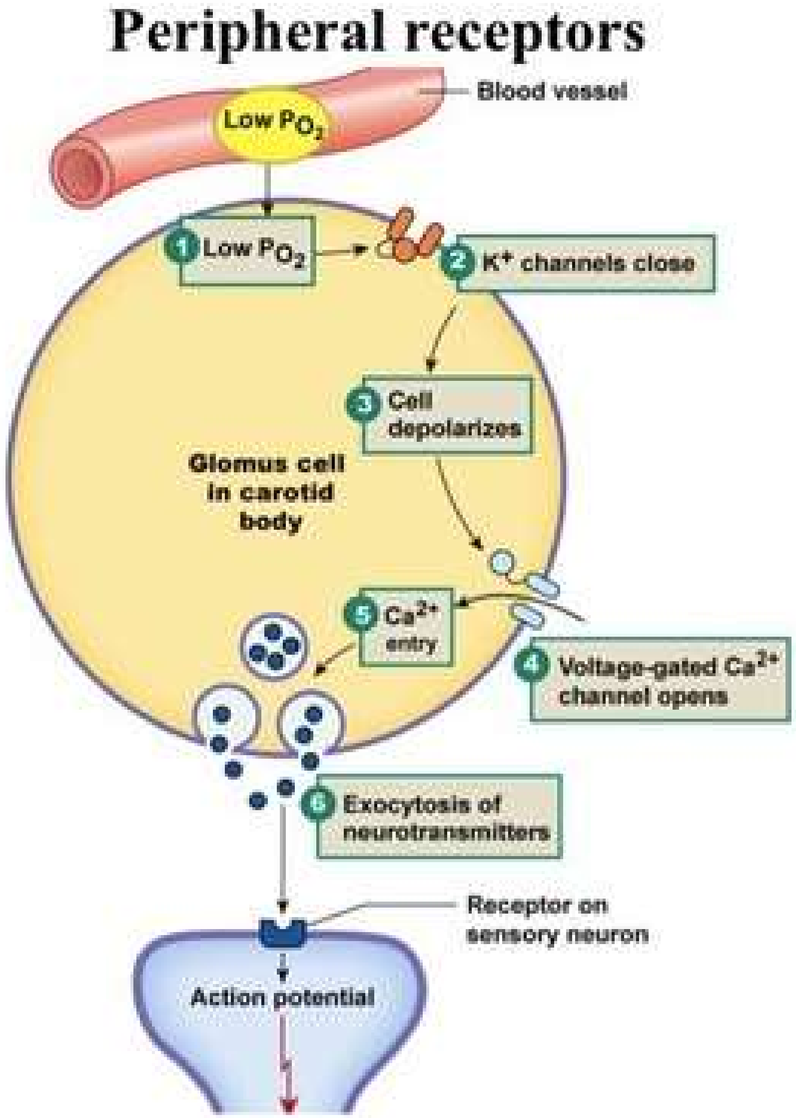
Vol % oxygen @ 1 bar	
18%	Slight increased breathing effort
16%	Flame lamp goes out
14%	Emotional upset, impaired judgement, faulty coordination
12%	Vomiting, cardiac ischemia
10%	Unconsciousness & death

Apart from hypercapnia....
Will hypoxia alone cause hyperpnoea?

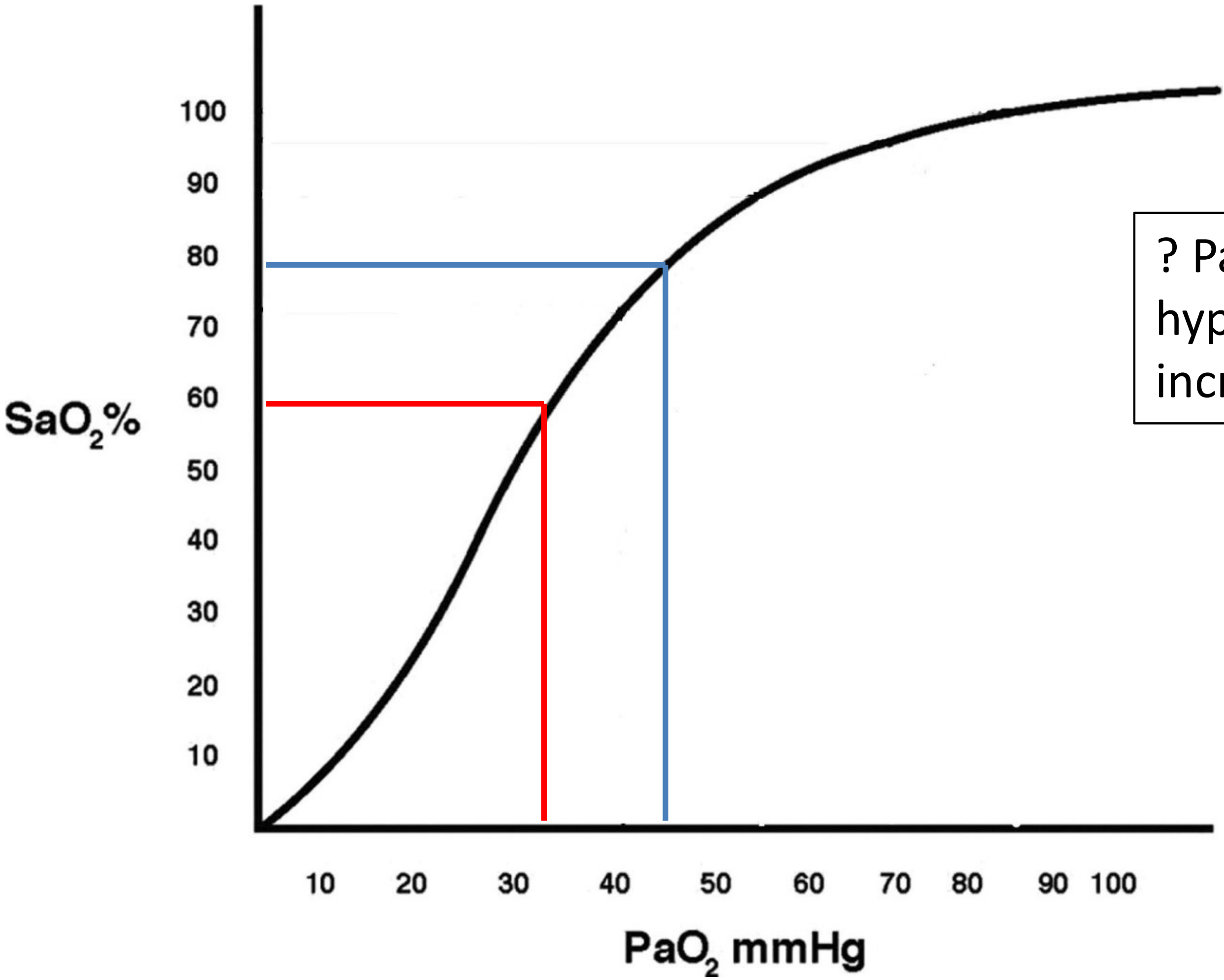
Hypoxic drive







ODC ? Rightward shift

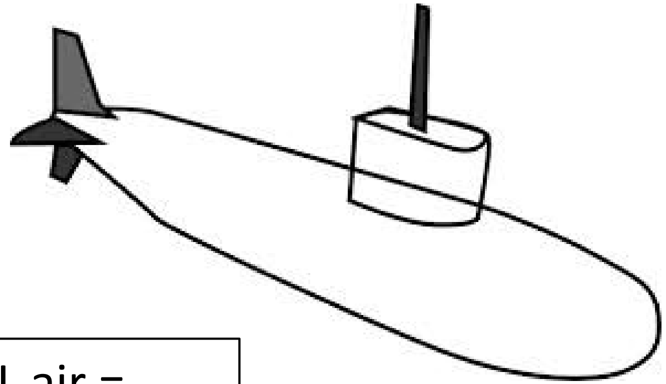


? $PaCO_2$
hyperventilation
increased insp CO_2

Putting it all together

	sPO_2	arterial PO_2	vol % inspired gas
minimal operational	80%	45 mmHg	14
survival	60%	35 mmHg	10

VO_2 = 400 ml/min
crew: 50
oxygen usage: 20 L/min
= 1200 L/h



air volume inside sub: 1200 M^3 = 1200.000L air = 252.000 L O_2

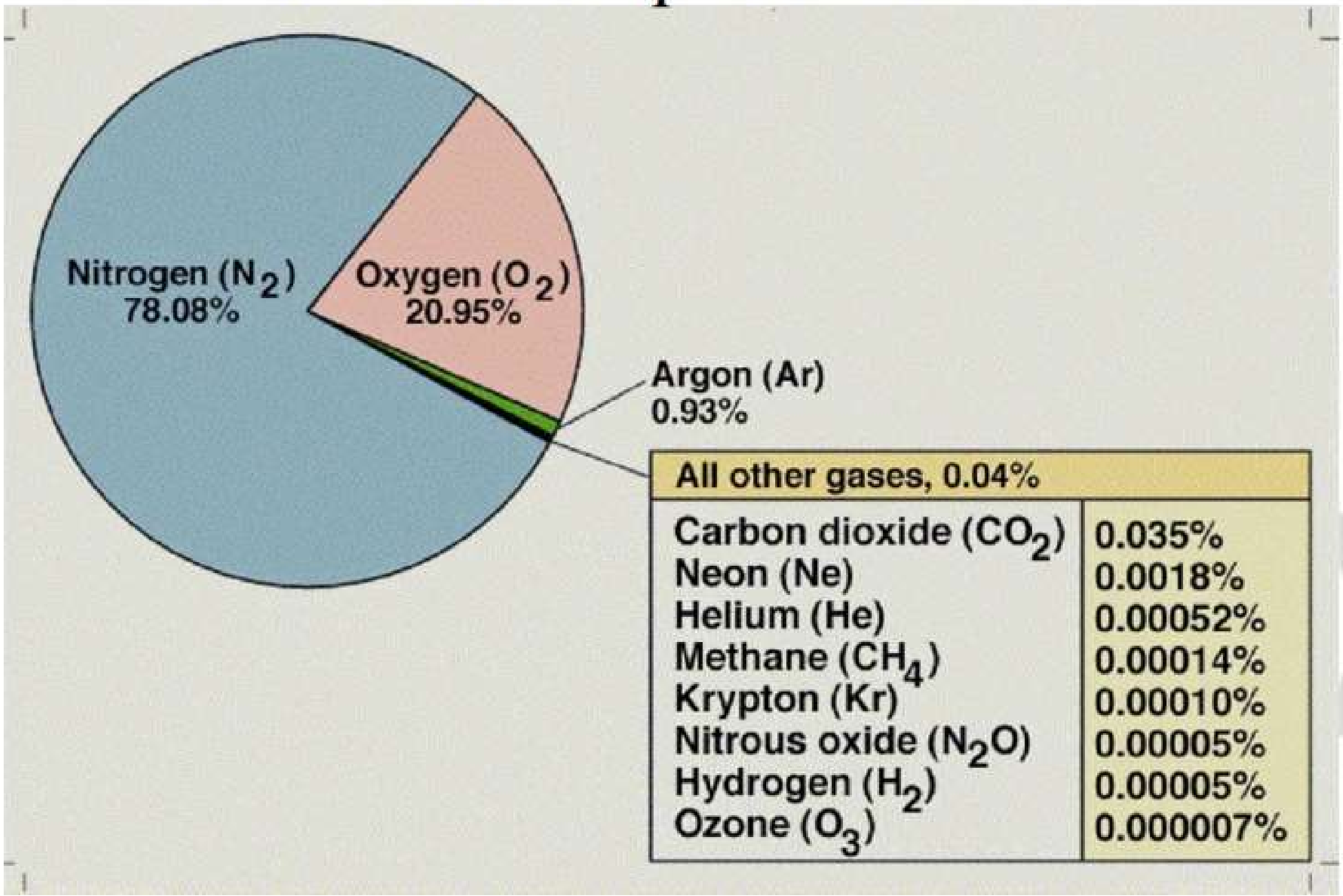
21% O_2: 252.000 L O_2 / 1200.000 L air
14% O_2: 168.000 L O_2 / 1200.000 L air
10% O_2: 120.000 L O_2 / 1200.000 L air

252.000 – 168.000 = 84.000 L used
252.000 – 120.000 = 132.000 L used

70 h
110 h

How about CO_2?

Composition of Dry Air in the Lower Atmosphere of Earth



Major constituents of dry air, by volume[6]			
Gas		**Volume**(A)	
Name	Formula	**in ppmv**(B)	in %
Nitrogen	N_2	780,840	78.084
Oxygen	O_2	209,460	20.946
Argon	Ar	9,340	0.9340
Carbon dioxide	CO_2	397	0.0397
Neon	Ne	18.18	0.001818
Helium	He	5.24	0.000524
Methane	CH_4	1.79	0.000179
Not included in above dry atmosphere:			
Water vapor(C)	H_2O	10–50,000(D)	0.001%–5%(D)

notes:

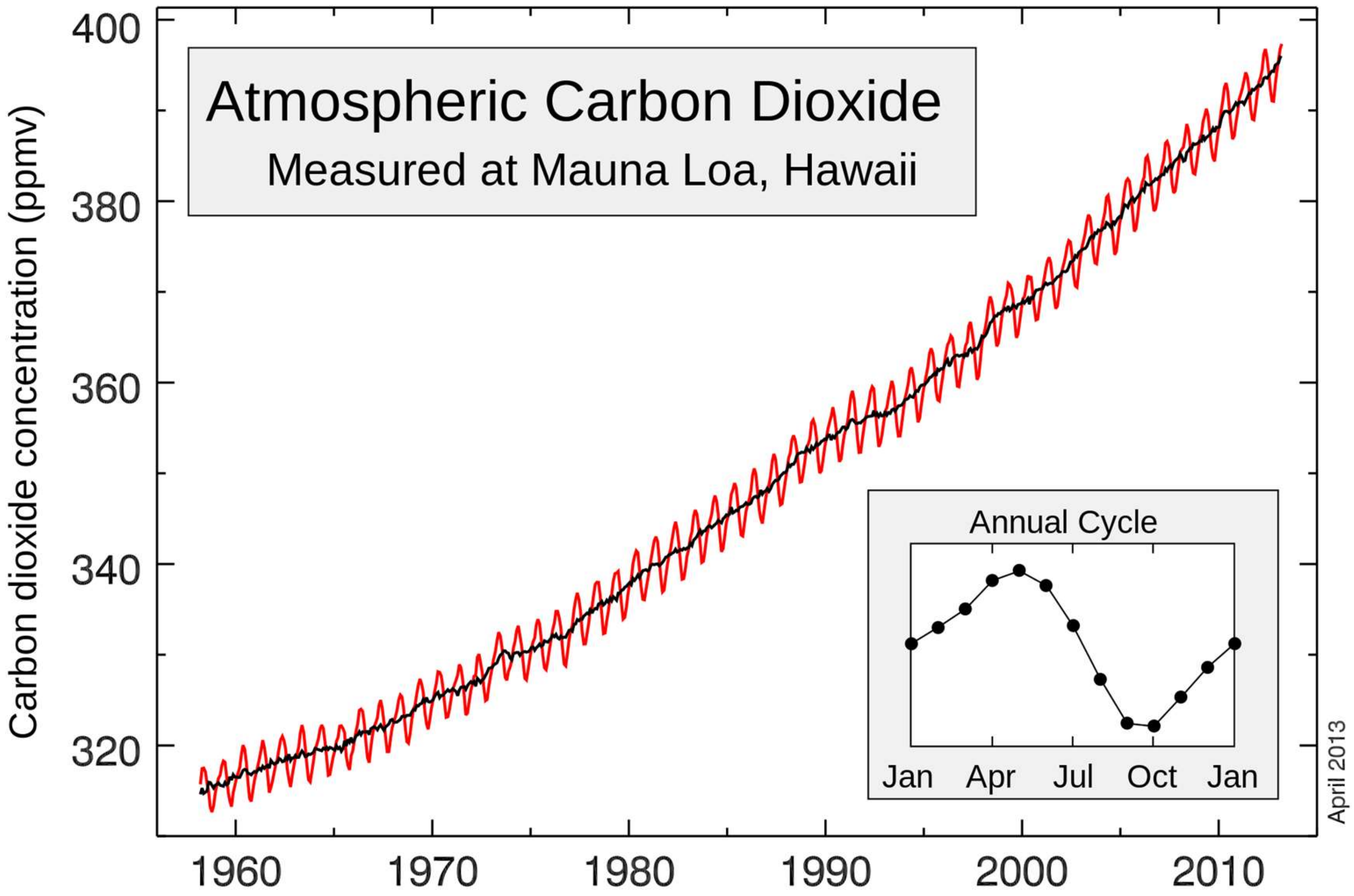
(A) volume fraction is equal to mole fraction for ideal gas only, also see volume (thermodynamics)

(B) ppmv: parts per million by volume

(C) Water vapor is about 0.25% *by mass* over full atmosphere

(D) Water vapor strongly varies locally[4]

How about the climate hype?



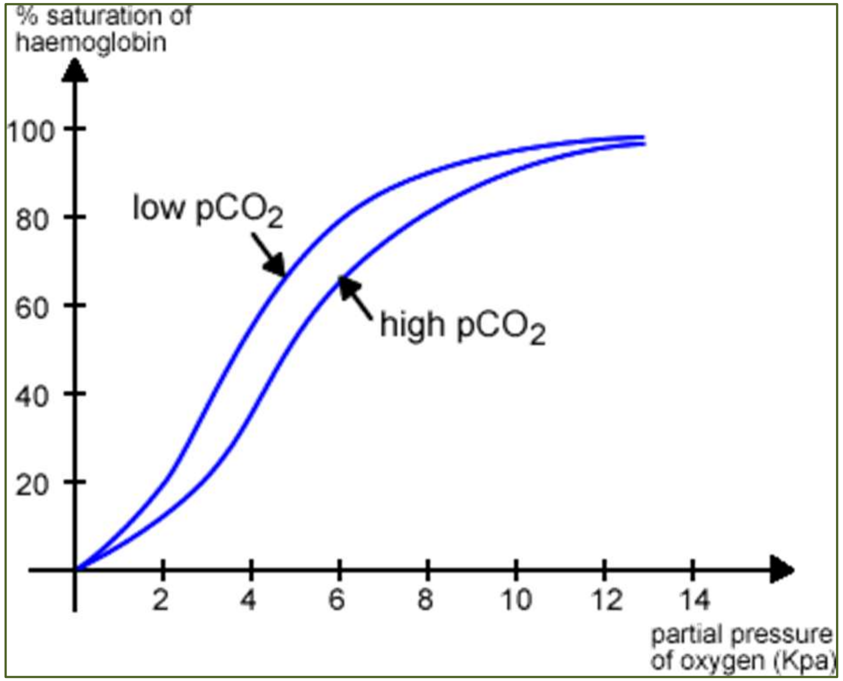
Clinical effects of hypercapnia

organ	physiology	symptoms	threshold
CNS	Vasodilation CBF↑ CBV↑	headache	
		narcosis	> 90 mmHg (12 kPa)
ventilation	setpoint	hyperventilation	Max stimulation at $paCO_2$ 100 mmHg
circulation	Sympathic drive↑ (also direct depressant effect)	Hypertension arrhythmias	
All organs	vasodilation	Flushed skin	

$PaCO_2$ & oxygenation

What is the influence of hypercapnia on oxygenation?

Right shift ODC



Alveolar O_2 displacement

$$P_AO_2 = (FiO_2 \times (P_{atmos} - P_{H2O})) - \left(\frac{PaCO_2}{RespQ}\right)$$

Partial pressure of alveolar oxygen

Fraction of inspired oxygen, 0.21 in room air

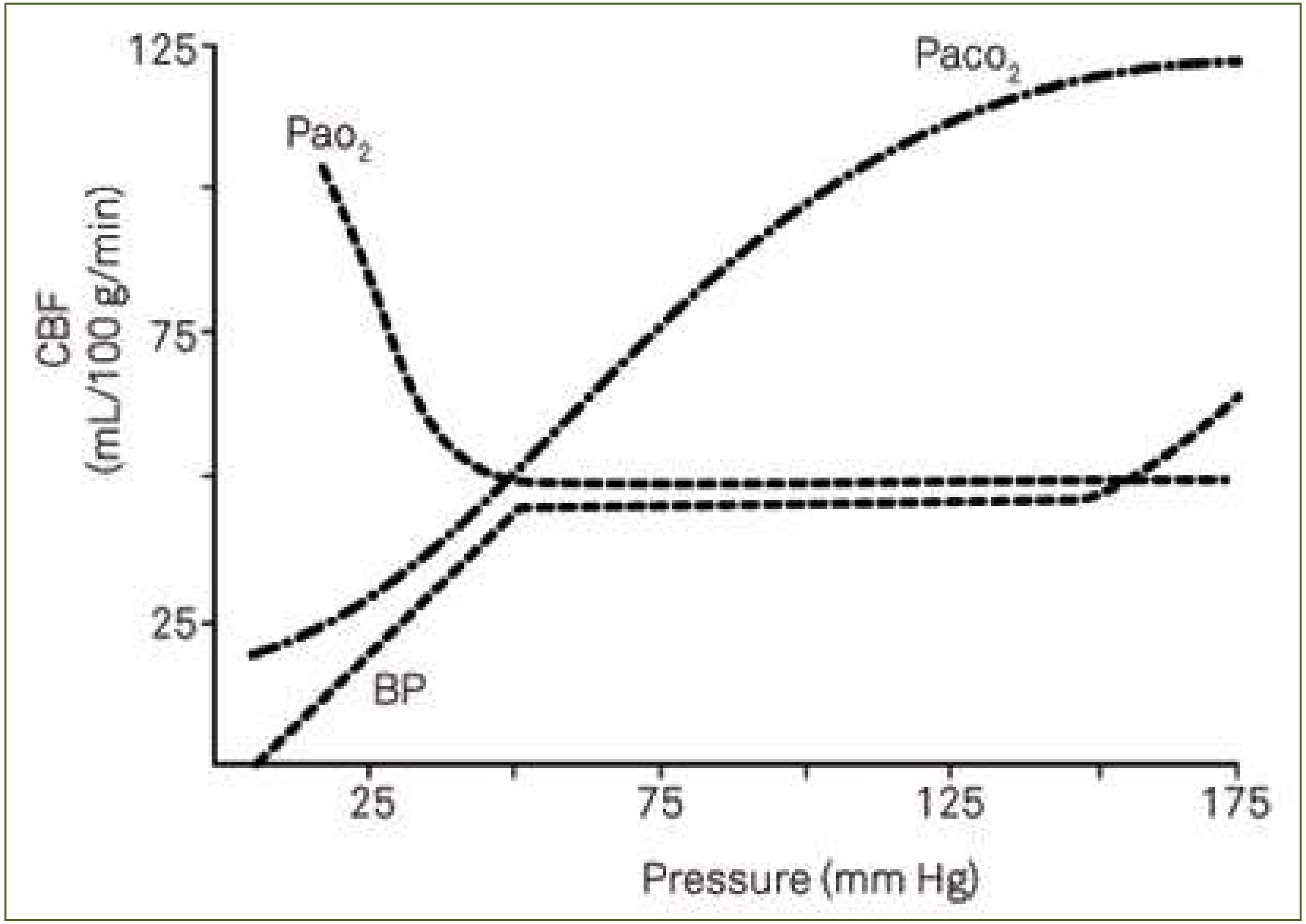
Atomspheric pressure: 760mmHg at sea level

H_2O vapour pressure in the alveolus: its usually 47mmHg at 37°

$PaCO_2$ from the ABG

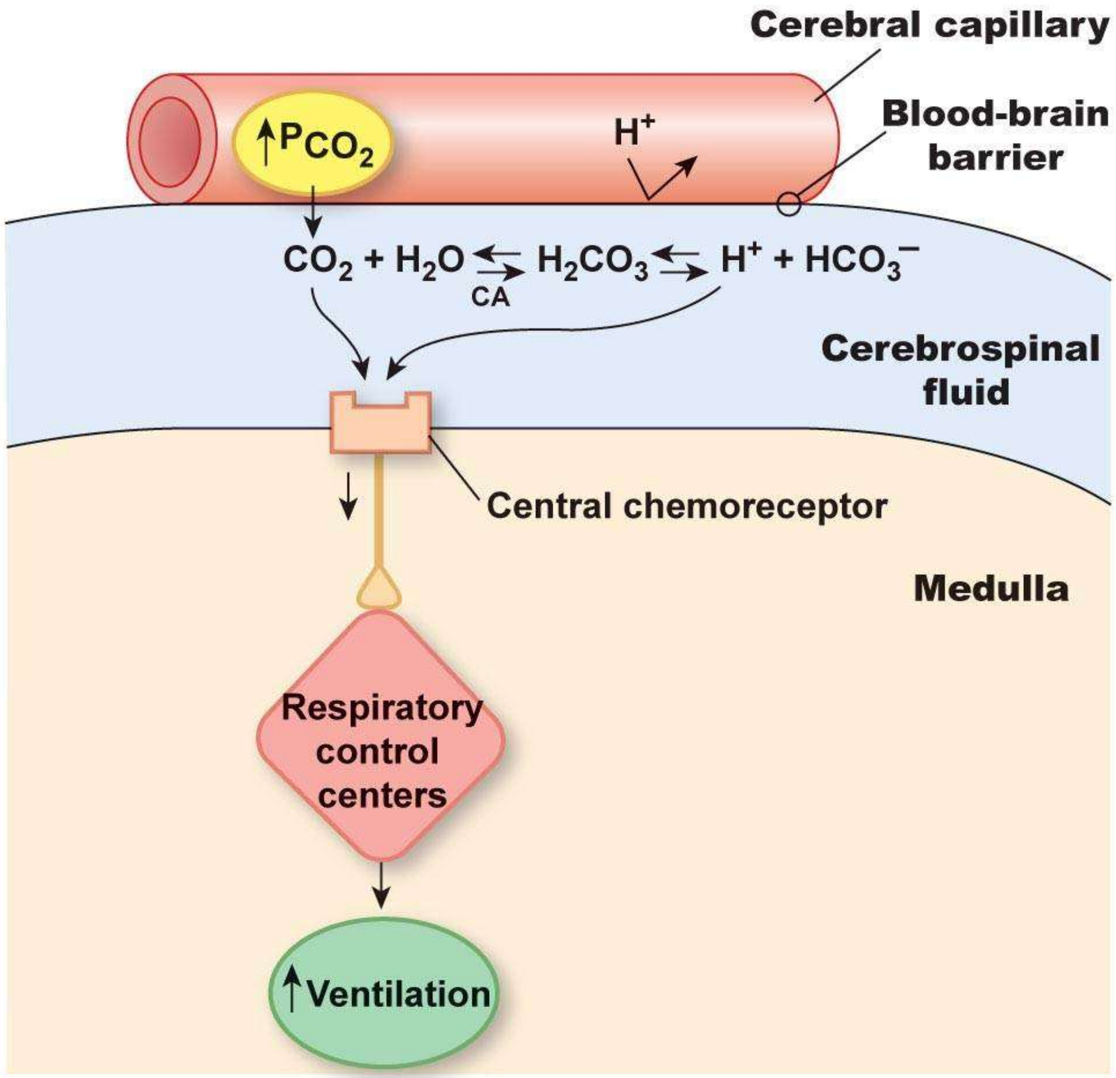
Respiratory quotient, which is usually 0.8

$PaCO_2$ & CBF

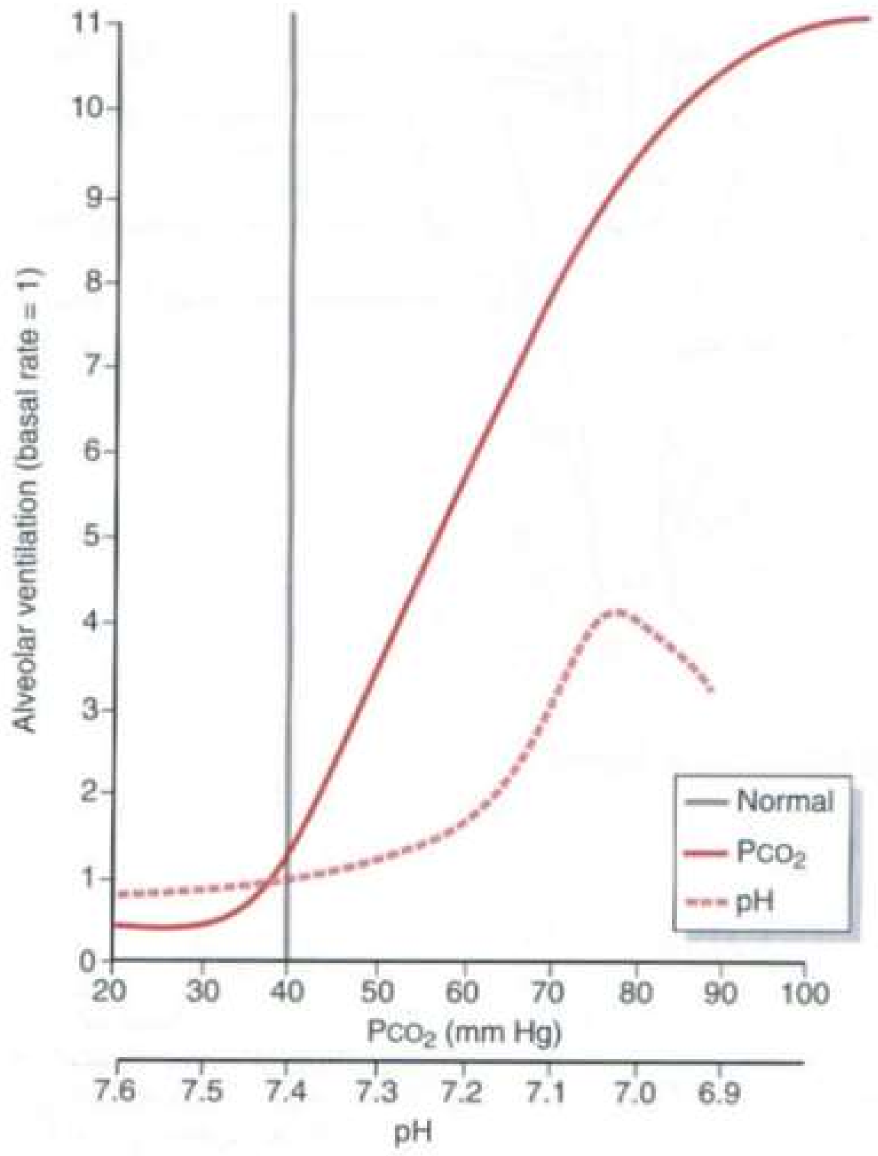


Why the headache?

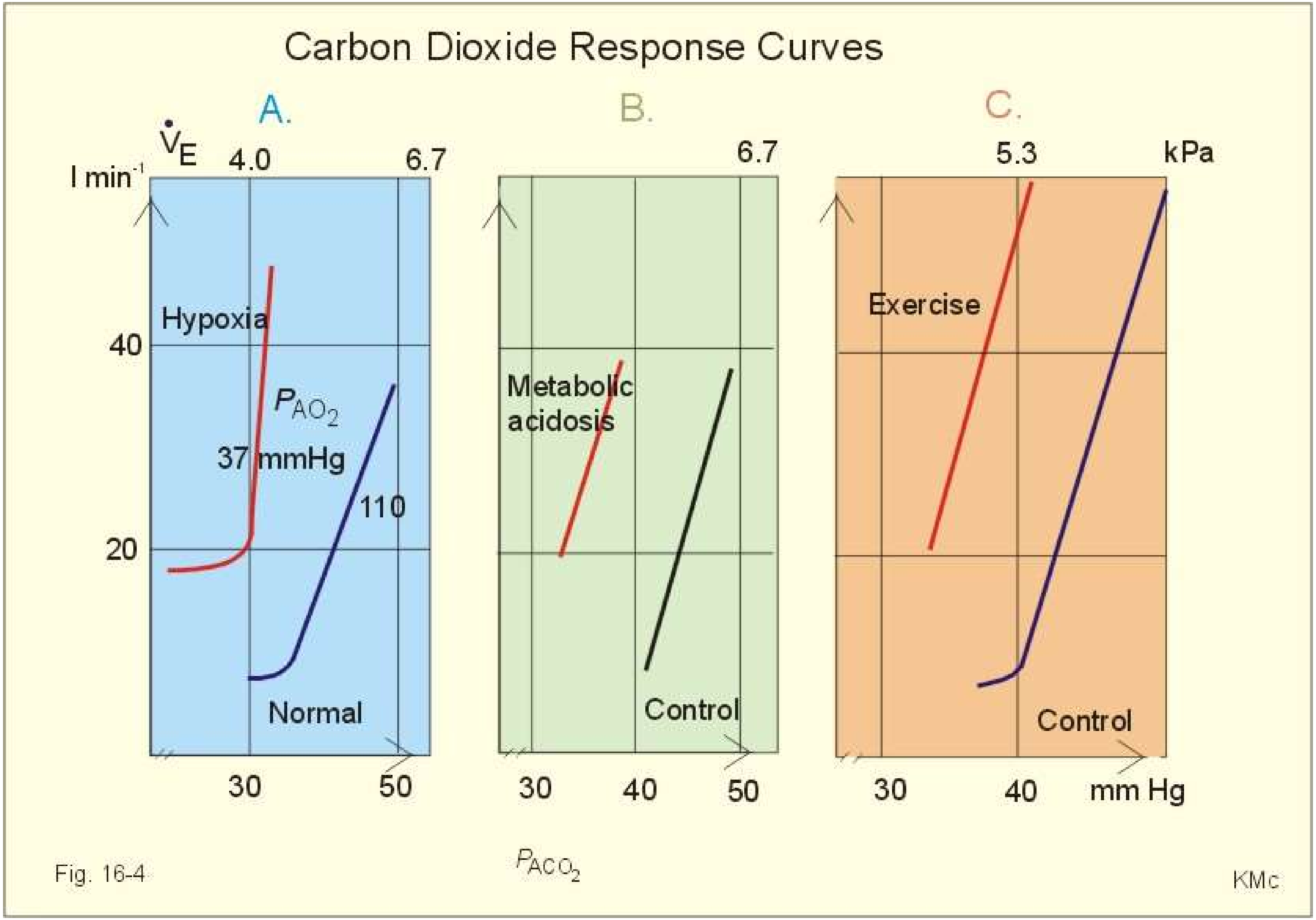
Central chemoreceptor



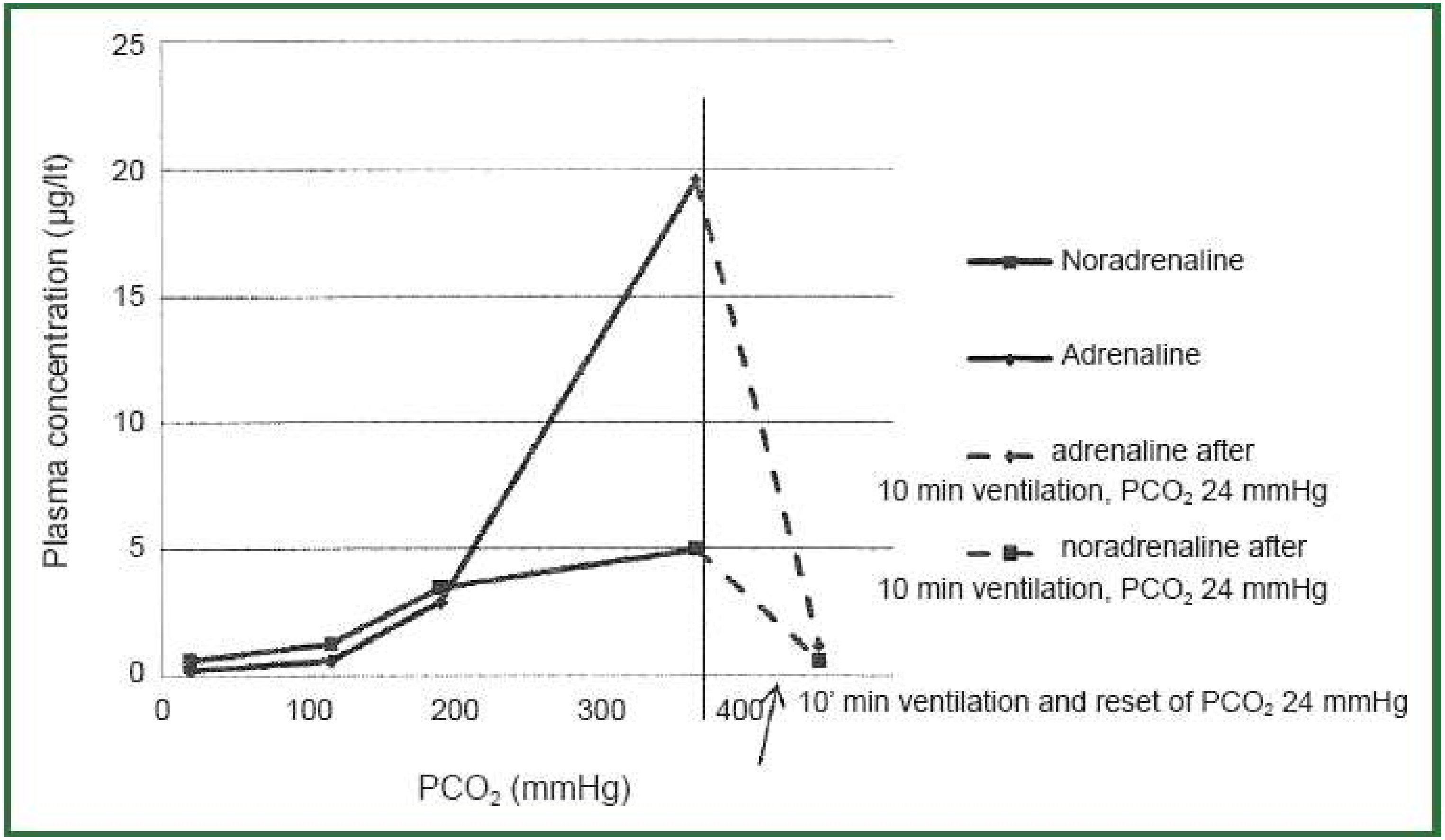
$PaCO_2$ & ventilatory drive



$PaCO_2$ & ventilatory drive

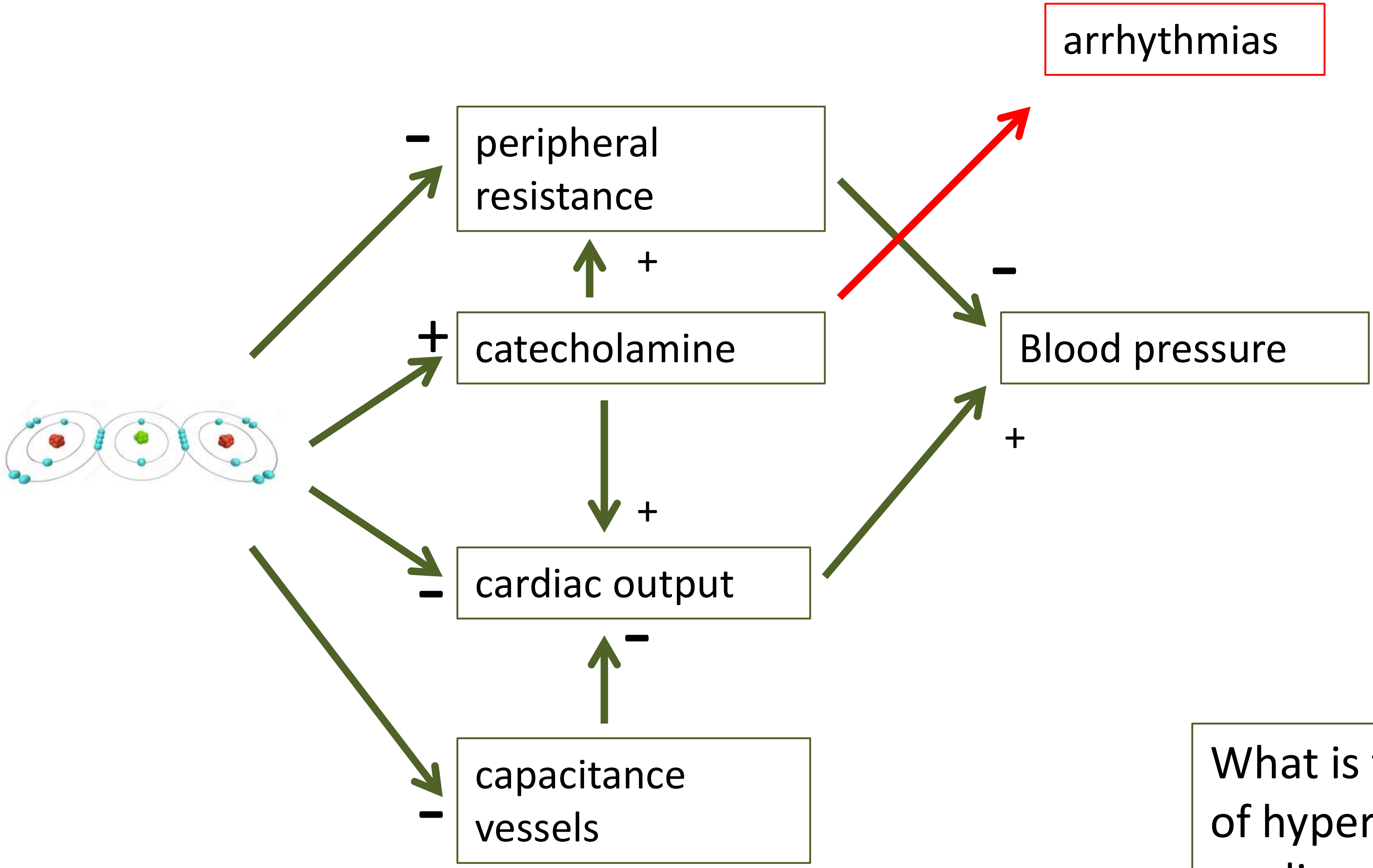


PaCO$_2$ & catecholamines



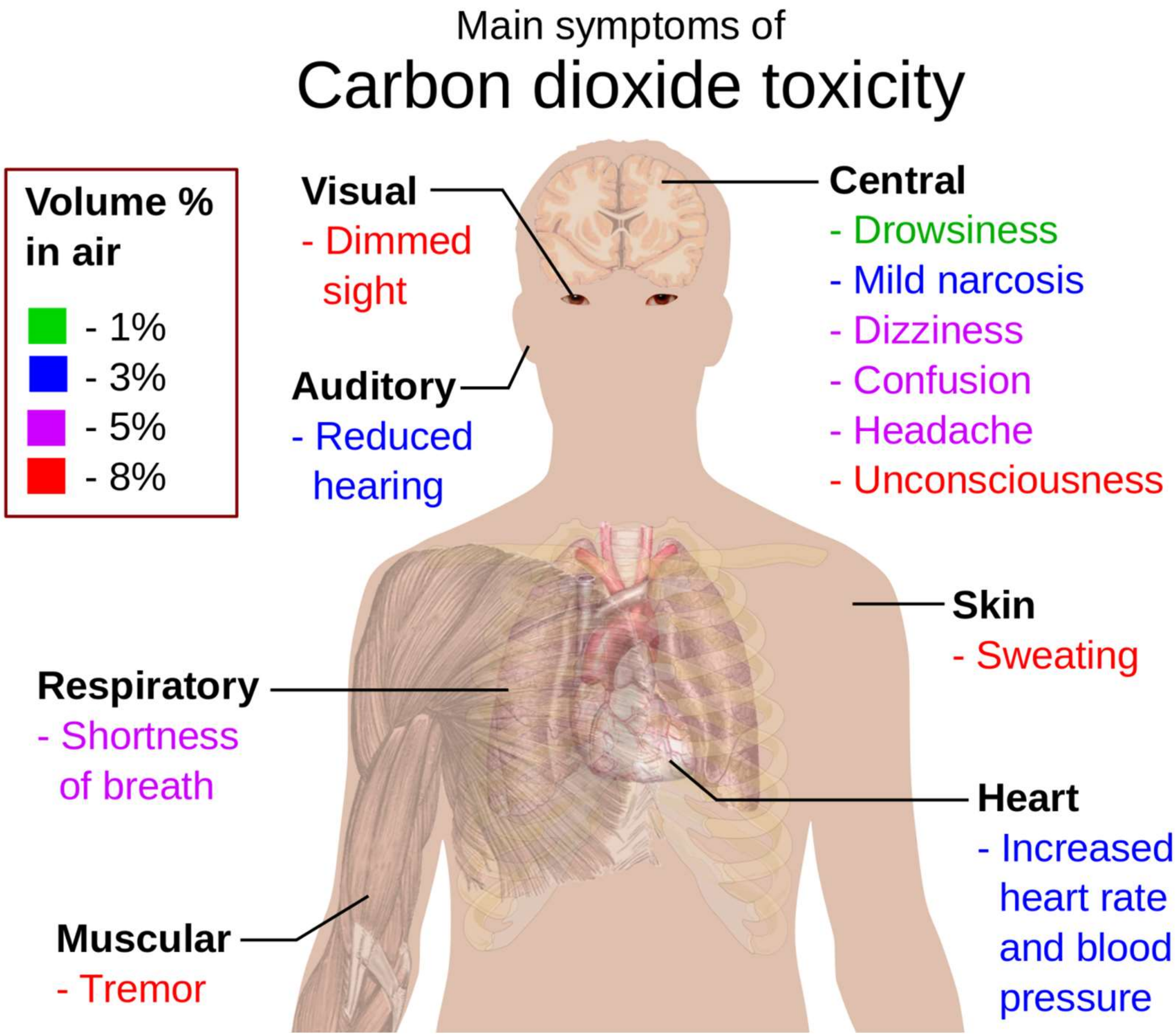
Hypercapnia during apnoe oxygenation in dogs

$PaCO_2$ & circulation

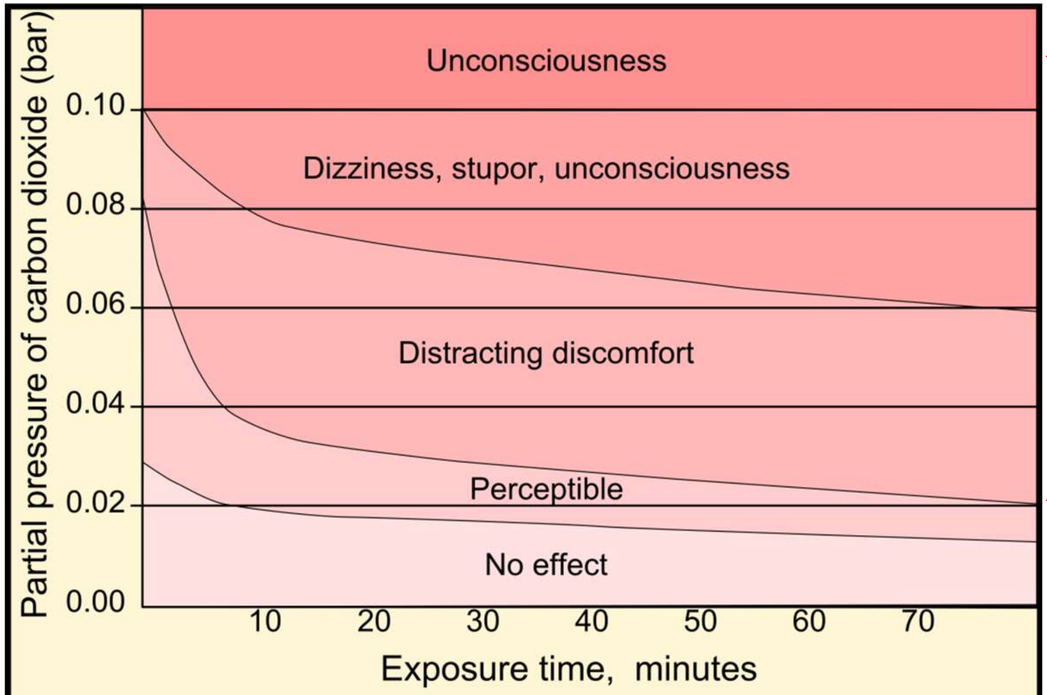


What is the influence of hypercapnia on cardiac output and blood pressure?

Symptoms of carbon dioxide toxicity



How high can you go?



Physiological effects of carbon dioxide concentration and exposure period

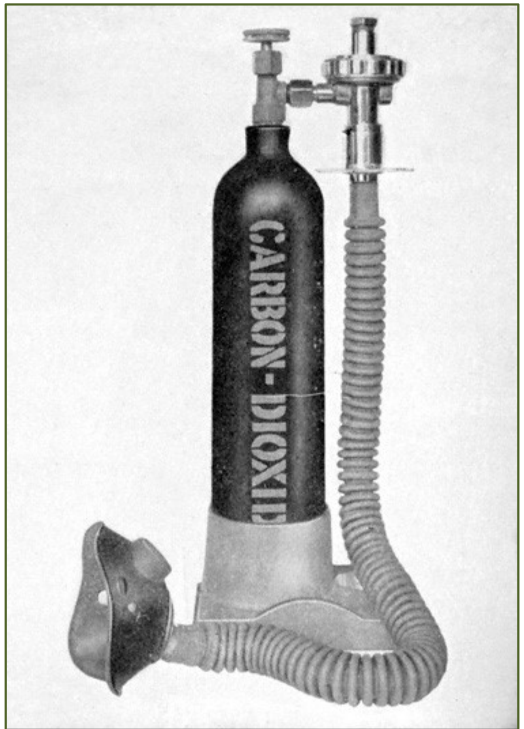
Unconsciousness, lethal level
> 0.1 bar = >10%

Maximum allowable inspiratory percentage
DISSUB 0.02% bar = 2%

	Volume %
Evacuate sub	2%
lethal	10%

Hypercapnia

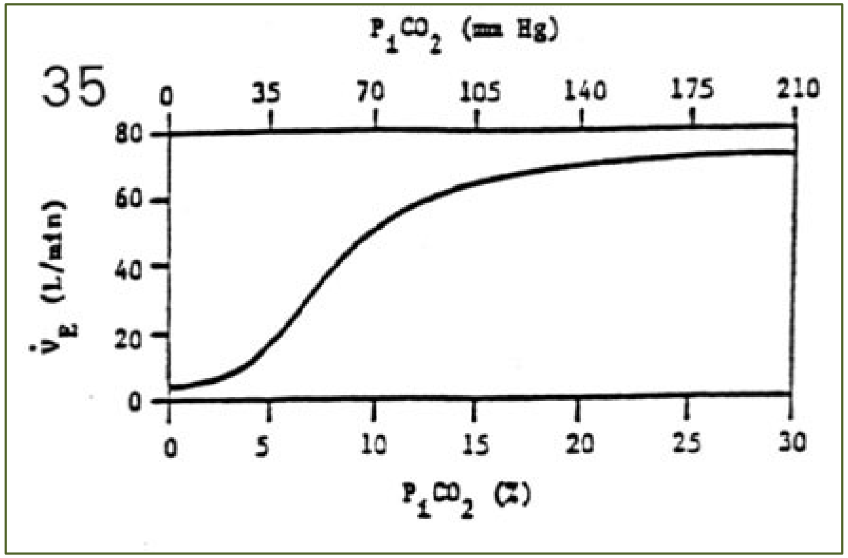
- endogenous: increase $PaCO_2$ 3-6 mmHg/ min (0.4-0.8 kPa/min
- exogenous: very rapid increase!
  - metabolic compensation takes time!
  - how long?
- carbogen



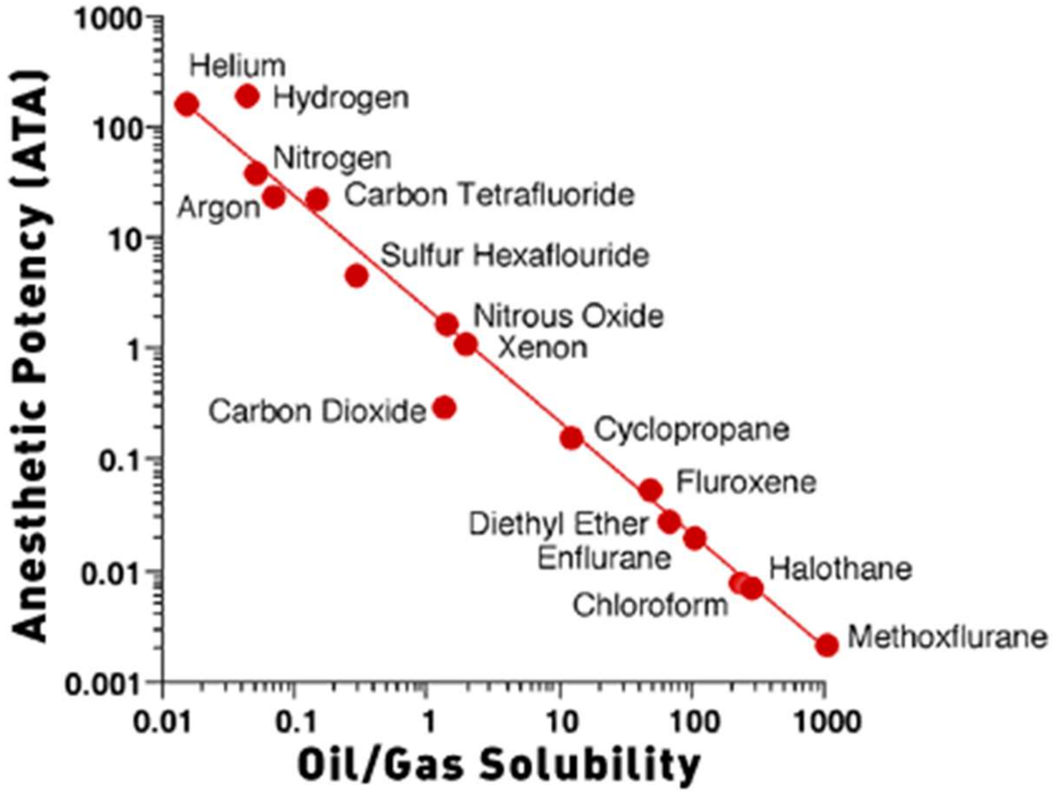
Carbon Dioxide Tank
Image from Oxygen and Carbon Dioxide Therapy (1934)

present use: to increase ophthalmic artery bloodflow

carbogen: 5% CO_2 & 95% O_2
Medunas mixture: 30% CO_2 & 70% O_2



Carbon dioxide as an anaesthetic

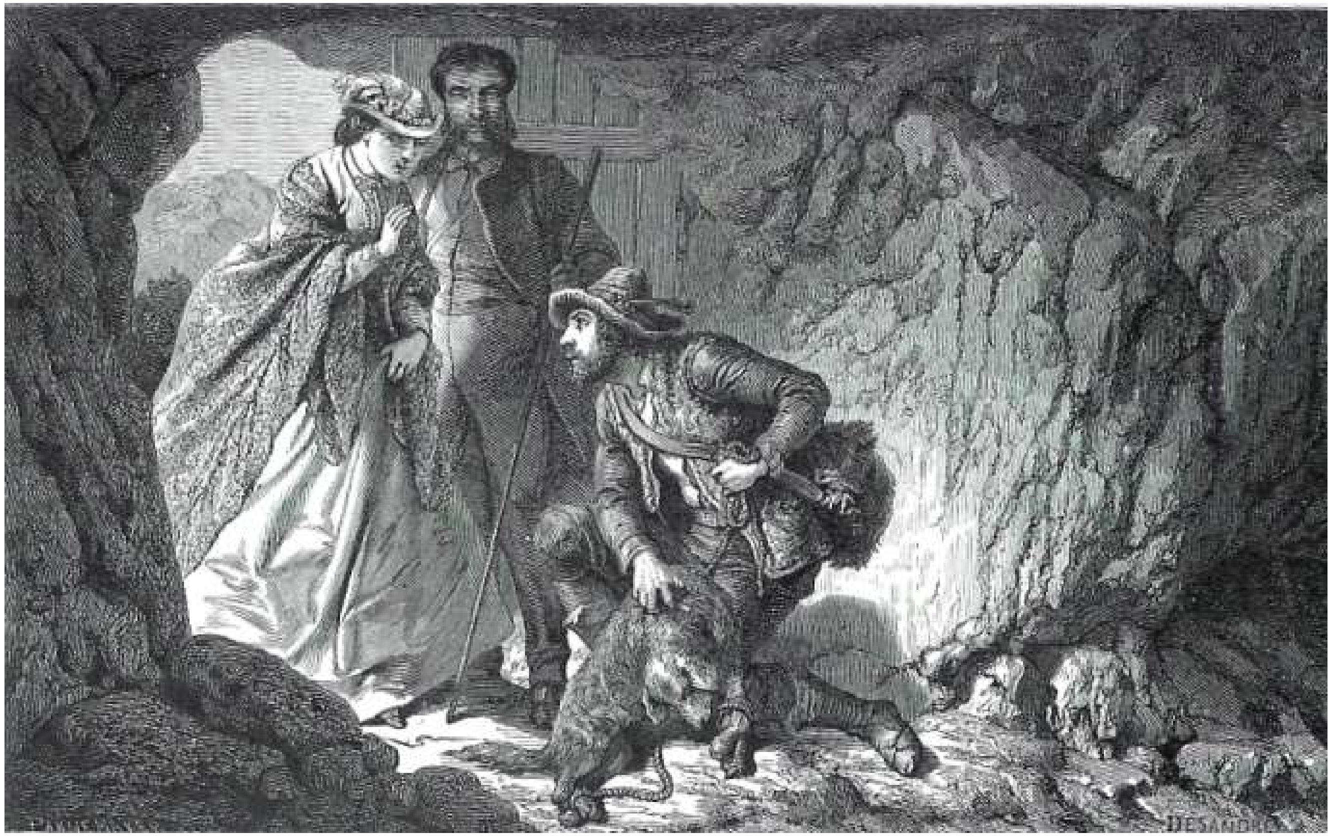


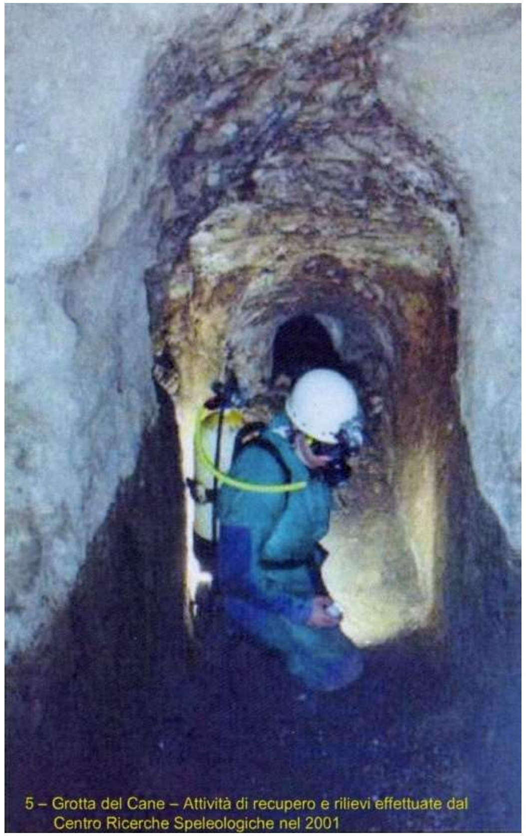
1824 Henry Hill Hickman
1928 Leake and Waters

Alteration intracellular ph

CO_2 30%: anesthesia and an isoelectric ECG but complicated by frequent convulsions!
still used for anesthesia of lab animals!

Grotto del cane



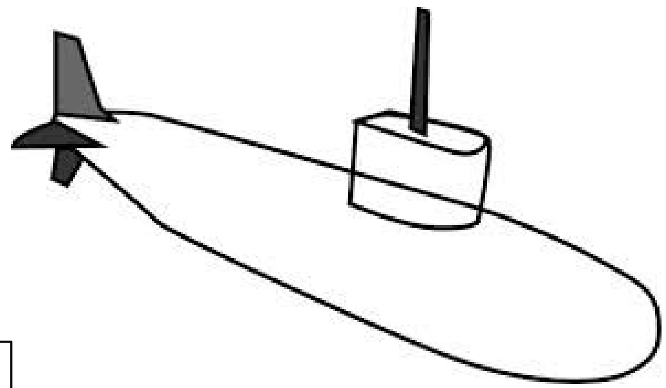


Cave is 10 m long
Volcanic release of CO_2
1 meter high CO_2 layer (near ground)

Putting it all together

Maximum	CO_2 vol % in air
operational conditions	2
survival conditions	10

CO_2 produced pp = 400 x 0.8 = 320 ml/min
Crew: 50
Total CO_2 production : 16 L/min
= 960 L/h



Air volume inside sub: 1200 M^3 = 1200.000L air
CO_2 content fresh air: 0

2 % CO_2: 2 x 12.000 = 24.000 L CO_2
10% CO_2: 10 x 12.000 = 120.000 L CO_2

24.000 : 960 =	25 h
120.000 : 960 =	125 h

Breathing in an enclosed space

Endurance	O_2	CO_2	
Operational limits	70 h	25 h	
Survival limits	110 h	125 h	

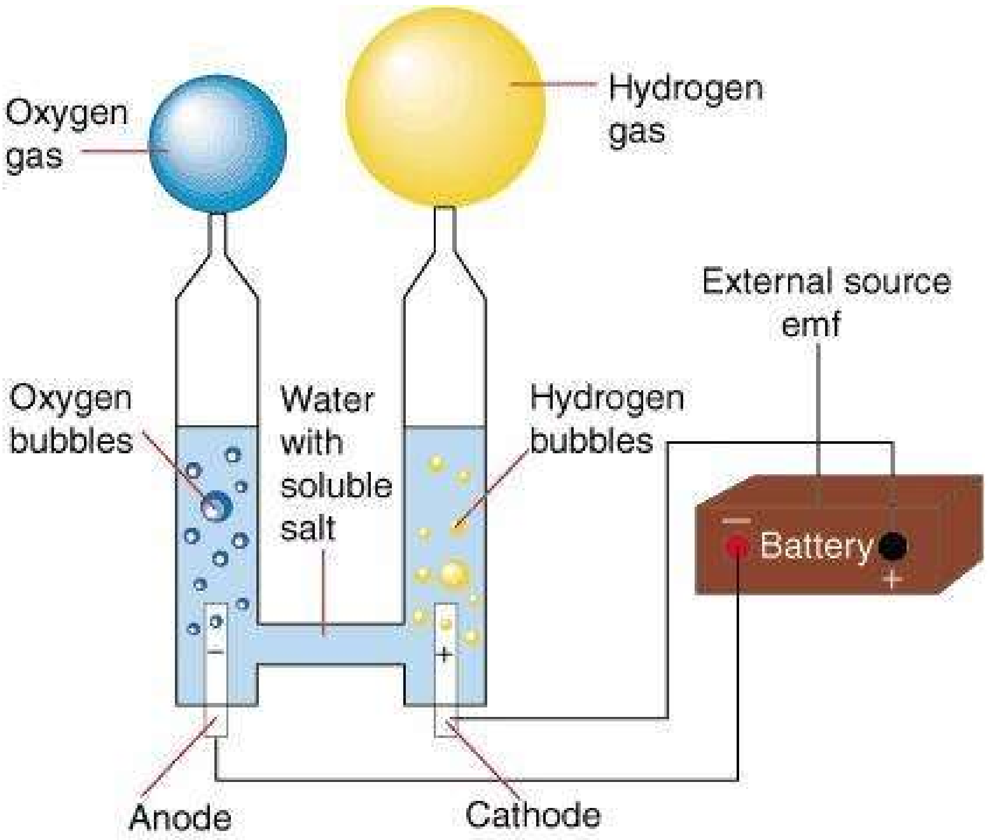
Carbon dioxide elimination

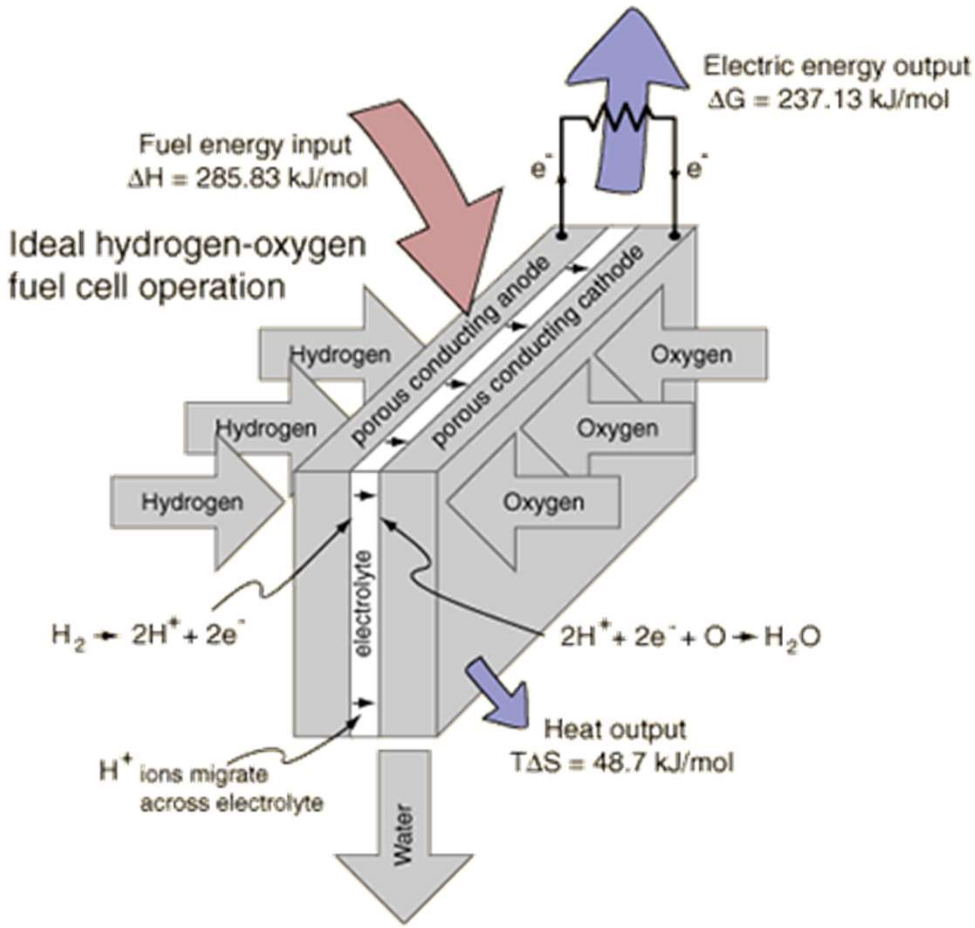
- surfacing
- scrubber
- regenerative CO_2 removal system

Oxygen supply

- surfacing
- electrolysis
- oxygen candle

Electrolysis

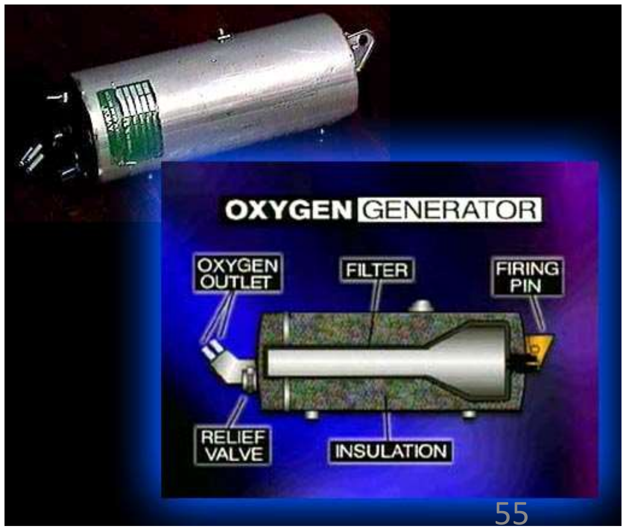




Fuel cell

Oxygen candle

- needs activation
- “burns” at 600^{o}C
- 15 minutes
- lithium perchlorate or sodium chlorate
- $2NaClO_3 + 2Fe \rightarrow 2O_2 + 2NaCl + 2FeO$



http://www.faa.gov/pilots/safety/pilotsafetybrochures/media/Oxygen_Equipment.pdf

Carbon dioxide absorption

The overall reaction is:
$CO_2 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O$ + heat (in the presence of water)
The reaction can be considered as a strong-base-catalysed, water-facilitated reaction.

Mechanism:
1) $CO_2 \rightarrow CO_{2\,(aq)}$ (CO_2 dissolves in water - slow and rate-determining)
2) $CO_{2\,(aq)} + NaOH \rightarrow NaHCO_3$ (bicarbonate formation at high pH)
3) $NaHCO_3 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O + NaOH$
- (NaOH recycled to step 2) - hence a catalyst)
- Each mole of CO_2 (44 g) reacted produces one mole of water (18 g).

	sodalime	baralyme	litolyme
catalyst	3% NaOH 1% KOH	20% BaOH	
CaOH	75%	80%	
H_2O	20%		
capacity	110-150 L/kg		450L/kg
advantage			Less weight

Lithium hydroxide

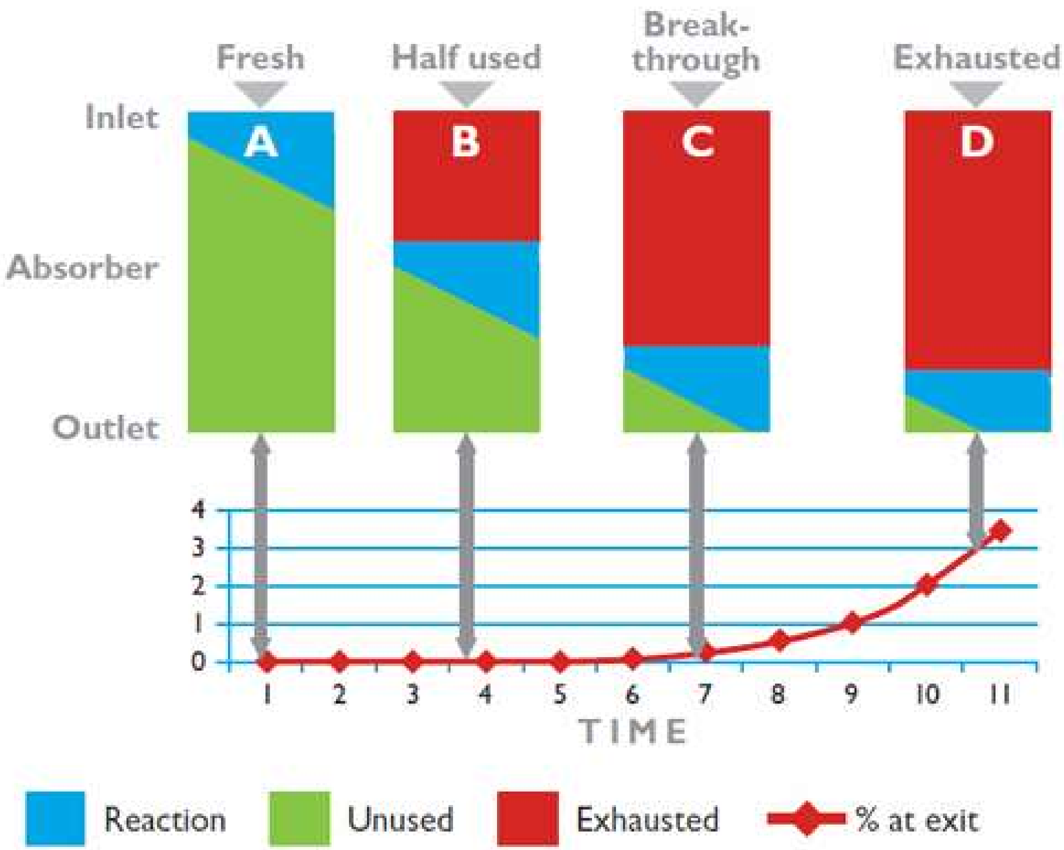
Lithium hydroxide (LiOH)

- $2\ LiOH(s) + 2\ H_2O(g) \rightarrow 2\ LiOH.H_2O(s)$
- $2\ LiOH.H_2O(s) + CO_2(g) \rightarrow Li_2CO_3(s) + 3\ H_2O(g)$
- The net reaction being:
- $2\ LiOH(s) + CO_2(g) \rightarrow Li_2CO_3(s) + H_2O(g)$
- advantages: higher capacity on a weight base

Lithium peroxide (Li_2O_2):

- $2\ Li_2O_2 + 2\ CO_2 \rightarrow 2\ Li_2CO_3 + O_2$
- advantages: even higher CO_2 absorbent capacity + oxygen production
- used in spacecrafts

scubber exhaustion



Indicator not useful in enclosed canister sytems!

- Time based scrubber change
- CO_2 % in air

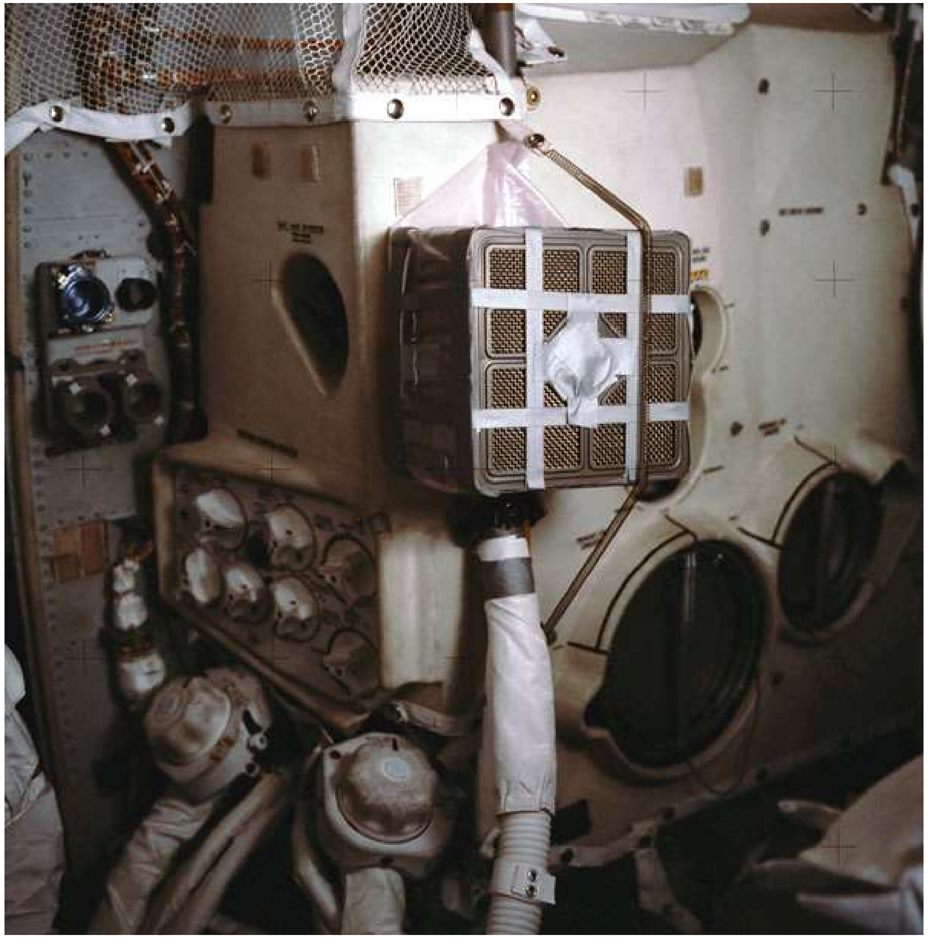
- $CaCO_3$ formation produces heat
- Temperature monitoring

CO_2 analyzer

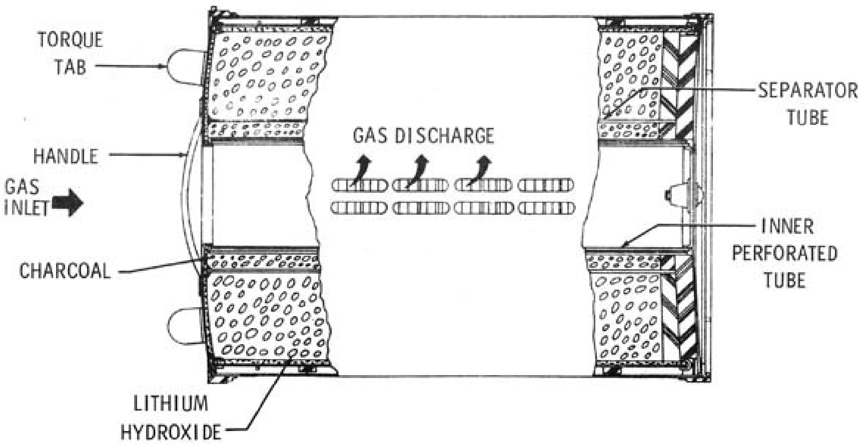
Dwyer CO_2 analyzer WWII

Absorber time left...?

Houston we have a problem........



Lithium Hydroxide (LiOH) Canister, Apollo Command Module, Block II improvised for use in the LM



Submarine scrubber capacity?

CO_2 production 960 L/h

Assume sodalime capacity 120 L CO_2/kg

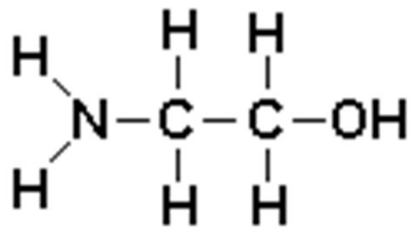
8 kg soda lime/h

Suppose we want to extend dive time 4 days = 96 h = 384 kg

But this assumes 100% efficiency!
In reality you probably need twice as much

20 kg drums x 19
limited storage inside a submarine!

Regenerative carbon dioxide removal system



monoethanol-amine (MEA)

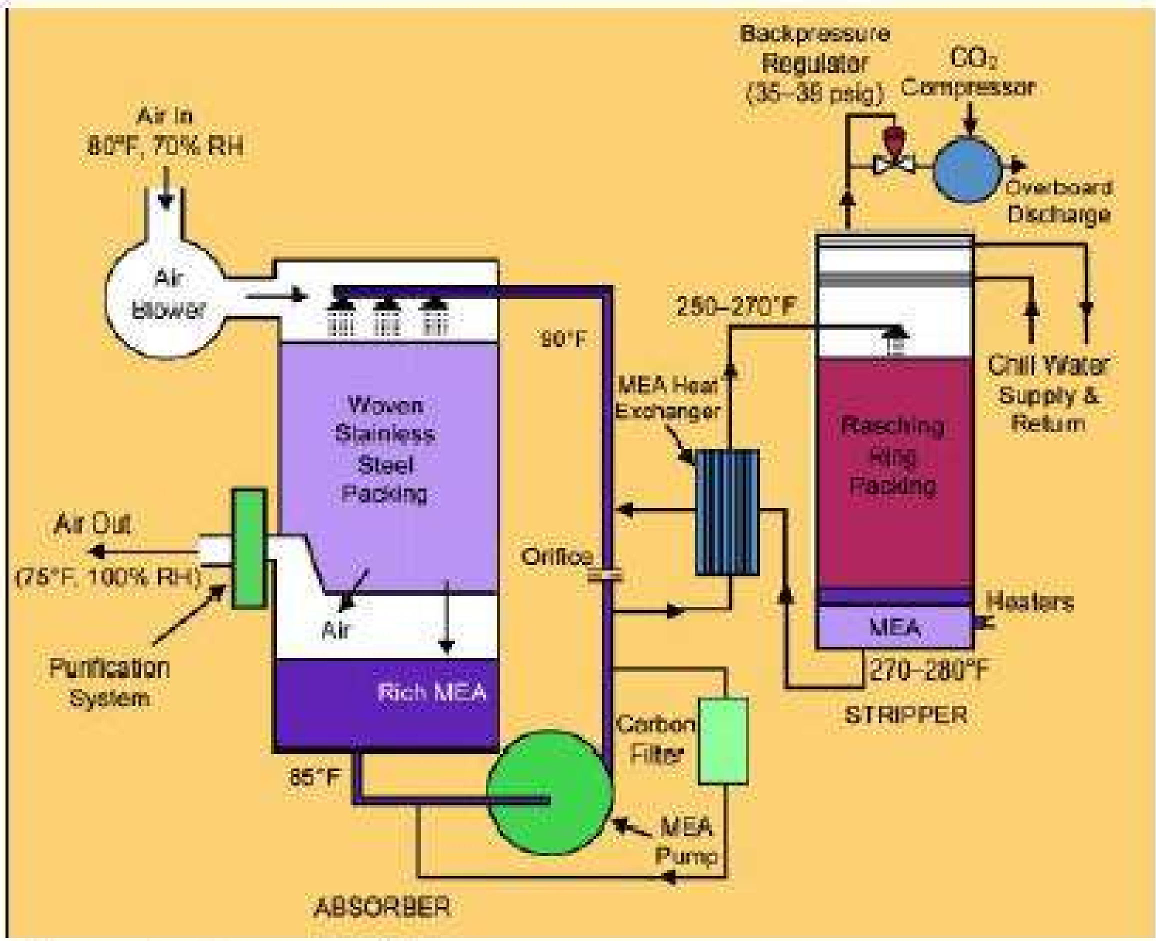


Figure 2: CO_2 scrubber.


The end.....
Slides available at www.mattijnb.nl