HYDRA IV

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HYDRA IV

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H Y D R A I V

COMEX S.A.

SCIENTIFIC MANAGEMENT

MARCH 1984

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F O R E W O R D

Operation HYDRA IV was carried out in the Hyperbaric Research Centre (HRC) at COMEX in Marseilles from November 14th to December 2nd, 1983. This experiment constitutes not only an important step in the conquest of the ocean depths but also an important world first. Because for the first time in history six divers in hyperbaric chambers breathed a hydrogen mixture at the record depth of three hundred metres, or nine hundred and eighty-five feet.

In line with its continuing investigation of great depths, and determined to maintain its world leadership in the realm of deep diving, COMEX has consistently attempted to, and succeeded in, surpassing its own previously established depth records, with operations such as PHYSALIE VI in 1972 (610 m for 1 hr 20 min), SAGITTAIRE IV in 1974 (610 m for 50 hrs) and ENTEX 9 in 1983 (450 m for 6 days and 610 m for 56 hrs).

To overcome the disadvantages of the now conventional gas mixtures, heliox and trimix, at depths below four hundred metres (thirteen hundred feet), a new breathing mixture had to be found which would enable divers to work safely at such depths and thus gain access to immense undeveloped virgin territories. One possible mixture, which had been known for some time but had never been tested on human beings at great depths was Hydrox, a compound of hydrogen and oxygen, and it was on this breathing mixture that COMEX was staking its bets for the coming years.

After a number of animal experiments using mice and monkeys, for the most part (COMEX's report, 1983 ; J.C. ROSTAIN, 1980), the decisive step was taken in July 1983 with HYDRA III when Henri G. DELAUZE, President of the COMEX Group, and Jean-Pierre BARGIARELLI, Director of COMEX Pro, carried out a dive to 91 metres' depth (300 feet) off the coast of Marseilles. At the bottom they breathed the Hydrox mixture for a few moments before starting their gradual ascent to the surface.

In view of the unmitigated success of HYDRA III, it was decided to go ahead with the research into the possibilities offered by Hydrox for conquering the great deep. A new project was conceived : HYDRA IV.

This experiment was written up in an exhaustive scientific report of which the present abridged version reproduces large parts, as well as the most important discussion ant the conclusions.

I N T R O D U C T I O N

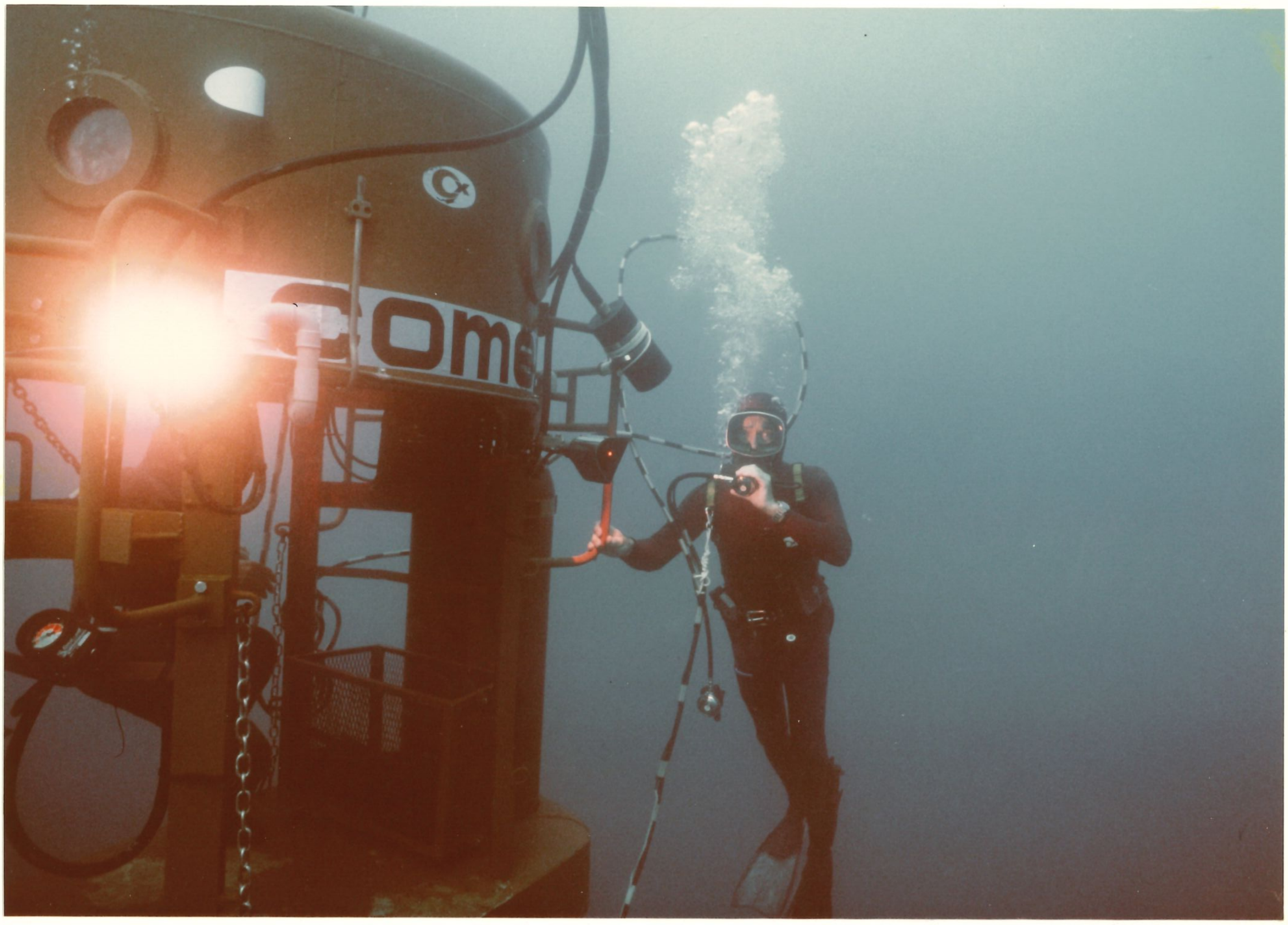
The history of hydrox began with the French chemist, LAVOISIER. In 1789 he gave guinea pigs under bell jars a mixture of "vital air" and "pure hydrogen gas" and observed that the animals remained in this milieu "for a long time without appearing to suffer from it".

One and a half centuries later, in 1941, CASE and HALDANE made the first experiments on human beings, and in 1944 and 45 ZETTERSTROM dove in the sea breathing hydrox to depths of 40, 70, 110 and 160 metres for several tens of minutes each time, without ill effects. The unfortunate death of this Swedish pioneer at the end of the fourth attempt was due, not to the breathing mixture, but to blow-up caused by a runaway winch which hoisted the platform on which the diver was working.

The systematic study of the biological effects of hydrox began in the UNITED STATES and FRANCE toward the end of the 1960s and has been pursued in a few laboratories up to the present time. Numerous experiments to pressure depths of as much as 900 metres on small mammals and monkeys, some carried out by COMEX, demonstrated that molecular hydrogen in a very pure state is not toxic. It was found, however, that it had, like nitrogen but to a lesser degree, narcotic properties which while disturbing were capable of diminishing the effects of High Pressure Nervous Syndrome.

After 1970, hydrox was breathed by scientists to a depth of 91 metres (in hyperbaric chamber by EDEL and FIFE and in the sea by DELAUZE and BARGIARELLI), but to prove the real advantages of hydrogen gas at 150 metres (as was done by ZETTERSTROM) and beyond for the time being to 300 metres, the depth range throroughly explored with heliox.

This was the aim fo HYDRA IV. Six divers, three professional divers and three scientists, breathed hydrogen-based mixtures for several hours at 120, 150, 180, 240 and 300 metres and underwent psychometric tests and comparative muscular exertion tests on heliox, on hydrox and on ternary mix at each depth.



HYDRA III : COMEX PRESIDENT H.G DELAUZE AT A DEPTH OF 91 M (298.5 F.S.W.), BREATHING HYDROX 97.5/2.5. (JULY 1, 1983).

THE ADVANTAGES OF HYDROX

HYDROGEN AND PRESSURE INTERACTIONS

For the past 15 years, roughly, deep divers working on underwater sites around the world have been breathing a mixture composed of helium and oxygen, heliox. The advantage of this mix is that it prevents the narcotic effect experienced by air divers below 50 or 60 metres' depth, which is caused by nitrogen.

But heliox has its limits, too. The first deep dives carried out on this gas revealed premonitory signs of a motor disorder manifested by hyperexcitability of the central nervous system. This disorder, called the High Pressure Nervous Syndrome, was described in humam beings by FRUCTUS, NAQUET, and BRAUER in 1969 following BRAUER, JORDAN AND WAY for animals in 1968.

To overcome the drawbacks of heliox, the HPNS, another mixture was proposed and used by P.B. BENNETT starting in 1974. This was a "Trimix" composed of oxygen, helium and a small percentage of nitrogen. It seems that the narcotic potency of nitrogen which is a limiting factor in air diving, counteracts the development of HPNS. This Trimix was adopted from 1976 to 1983 for the COMEX-FRENCH NAVY operations, from JANUS IV in the sea to ENTEX 8 (12 days at 450 m) at the GISMER Hyperbaric Centre.

But the density of trimix at high pressures beyond 300 metres' depth increases the ventilatory work of the diver, thereby reducing his possibilities of muscular work and consequently his efficiency. With hydrogen it is just the opposite, the ventilatory resistance is lowered and if, as is hoped, its narcotic potency - lower than that of nitrogen but greater than that of helium - is also anti-HPNS, the advantages of a mixture containing hydrogen will be doubled at 300 metres and well beyond !

- 1/ improvement of the respiratory function,
- 2/ reduction of the high pressure nervous syndrome.

HYDROGEN AND SAFETY

H_2 is a combustible gas which ignites in air when its voluminal concentration is between 4 % and 74.5 %. When mixed with oxygen the flammability range becomes much greater : the lower limit remains around 4 % but the upper limit increases to 94 or even 95 % at a pressure of some tens of bar. In such a case the mixture is highly explosive and very little energy is needed to ignite it. For city gas, for instance, ten times the energy is required. When, however, the concentration of oxygen in the mixture is less than 4 %, it is no longer inflammable. The hydrox mixture used in HYDRA IV, 98 % hydrogen/2 % oxygen, is therefore below the limit of flammability.

Furthermore, the experimental apparatus was designed to prevent any possible leakage of the hydrox into the heliox atmosphere of the hydrosphere and living chambers.

HYDROX : ECONOMIC ASPECT

Economically, hydrox, which has a very high percentage of hydrogen, is extremely attractive.

For helium is a very expensive gas. By the cubic metre it costs F.F. 60 in France at present and F.F. 200 in certain other countries, like Brazil, and it is not unusual for a worksite to consume a thousand cubic metres per day.

Hydrogen, on the other hand, sells for one-tenth to one-thirtieth the price of helium, the price difference being due to the methods required to produce the two gases.

Helium is a fossil gas, with all the constraints restrictions and monopolies that implies. Whereas hydrogen is a manufactured gas which can be produced at will in a variety of ways in all of the industrialized countries. There is no problem regarding supply, therefore, and at a price which is definitely democratic.

THE GOALS OF OPERATION HYDRA IV

This operation, which was completely experimental, enabled us to tackle most of the problems posed by respiration of hydrox in deep sea diving, i.e. :

- possible toxicity of hyperbaric hydrogen down to a pressure depth of 300 m for bottom times of an hour or less and 150 m for bottom times of 2, 4 and 6 hours,
- narcotic potency of hydrogen compared to nitrogen,
- study of pulmonary ventilation on hydrox, both awake-at-rest and during muscular exertion,
- possible anti-HPNS effect : would breathing hydrox permit divers to avoid, to a greater extent than heliox or trimix, motor disorders resulting from the High Pressure Nervous Syndrome ?
- heat loss,
- isobaric conterdiffusion after gas switching,
- voice modification.

In an effort to obtain replies to the most important questions, several different methods of investigation were used :

- behaviour analysis,
- psychometry,
- cardio-respiratory functional evaluation,
- comparative electroencephalography,
- blood and urine biology,
- doppler detection of circulating bubbles,
- echograph detection of stationary bubbles,
- voice recording.

S T A F F

THE DIVERS

The six divers were divided into two teams of three :

Team A

GIRAUD Marcel (A1) - 45 years old - French - Professional diver
GUERRIER Gérard (A2) - 27 years old - French - Engineer
LE MIRE Jacques (A3) - 37 years old - French - Doctor

Team B

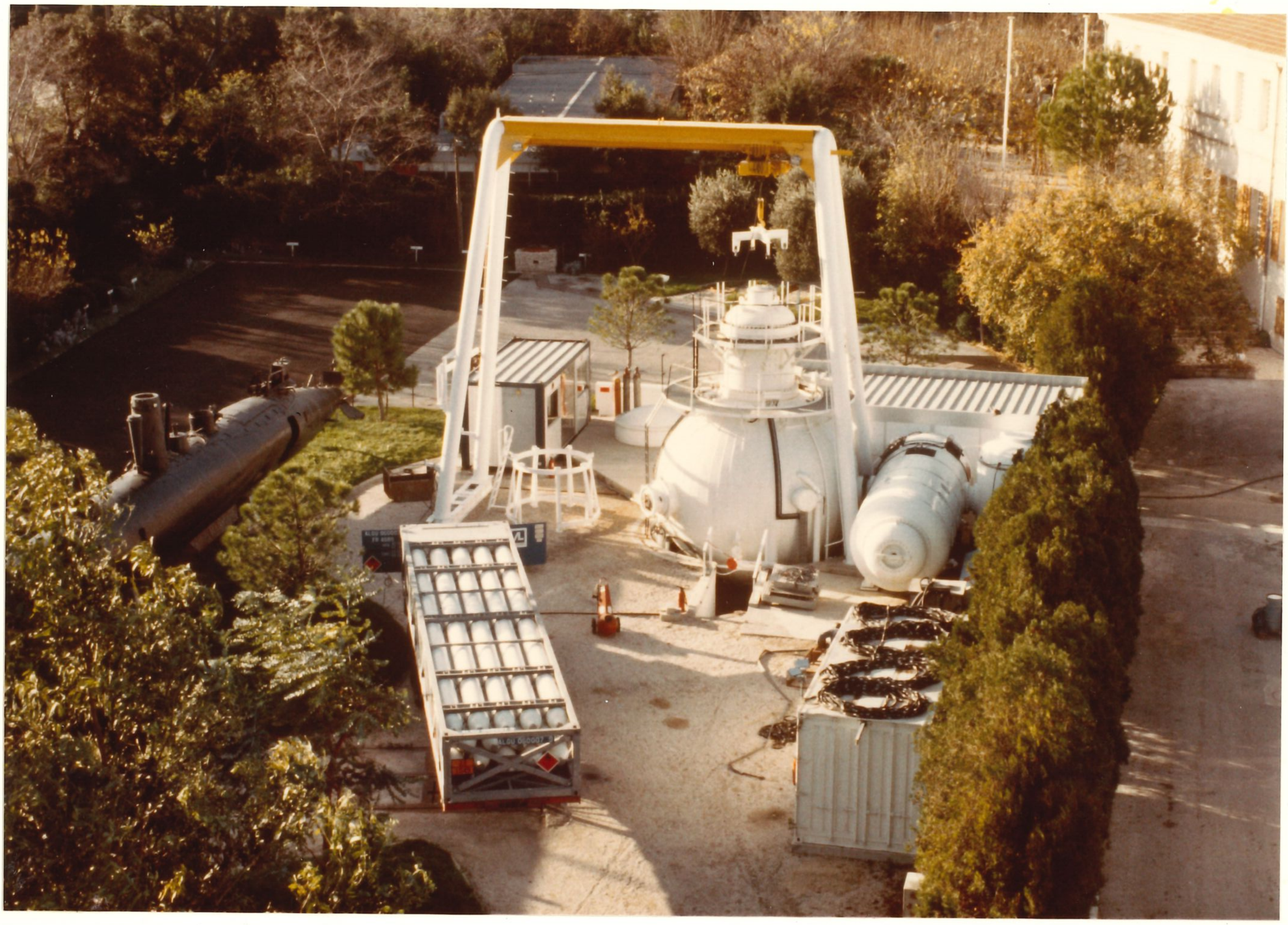
SCHNEIDER Louis (B1) - 32 years old - French - Professional diver
NORMAN Gerry (B2) - 40 years old - British - Professional diver
CROSS Maurice (B3) - 37 years old - British - Doctor

Replacement diver :
TRELLU Hubert - 27 years old - French - Doctor

SCIENTIFIC TEAMS

- Under the direction of COMEX President H.G. DELAUZE :
  The COMEX scientific and technical departments, the Hyperbaric Research Centre and the security and safety services, as well as COMEX HOULDER RESEARCH.

- Non-COMEX participants :
  - the Medical Services of the French armed forces : CEPISMER, CERB, CERTSM, GISMER ;
  - INPP of the French Ministry of Labour ;
  - GIS of hyperbaric Physiology, of the CNRS ;
  - Universities of OXFORD and RENNES and CANTINI Cardiological Centre ;
  - The MONTGRAND Medical Centre and the GP of FFMK.



COMEX HYPERBARIC RESEARCH CENTER - VIEW OF THE HYDRA IV LAYOUT -

IN THE CENTER : THE HYDROSPHERE WITH LIVING CHAMBER CONNECTED TO IT
FOREGROUND : HYDROX 98/2 TRAILERS

E Q U I P M E N T

HYPERBARIC COMPLEX

Part of the COMEX Hyperbaric Research Centre facilities in Marseilles were used, including :

Unit N° 1 : The hydrosphere, a pool-chamber 5 metres in diameter containing :

- a gaseous space filled with heliox
- a circular floor partially covering the pool
- the pool filled with water thermostatically controlled to about 30°C,
- in the centre, a transparent plastic dome under which the comparative tests were carried out on heliox and hydrox, in the dry or under water (see Figure 1).

Unit N° 2 : an 8-person living chamber with communication to the hydrosphere "lab" chamber,
a control room for both units, outside the hyperbaric system.

The hydrox mixture was circulated through an independent circuit installed in accordance with safety standards for the use of hydrogen.

GASES USED

- Heliox was used for saturation with 400 mbar O_2 at all storage depths : 120, 180, 240 and 300 metres.

- For the comparative tests under the dome using heliox and hydrox in the dry and in the wet, the breathing mixtures were :

  - helium/oxygen with 2 % O_2
  - hydrogen/oxygen with 2 % O_2

  The PIO_2 therefore were variable between 260 mbar (120 m) and 620 mbar (300 m), depending on the depth, but were the same for the two breathing mixtures at the same depth.

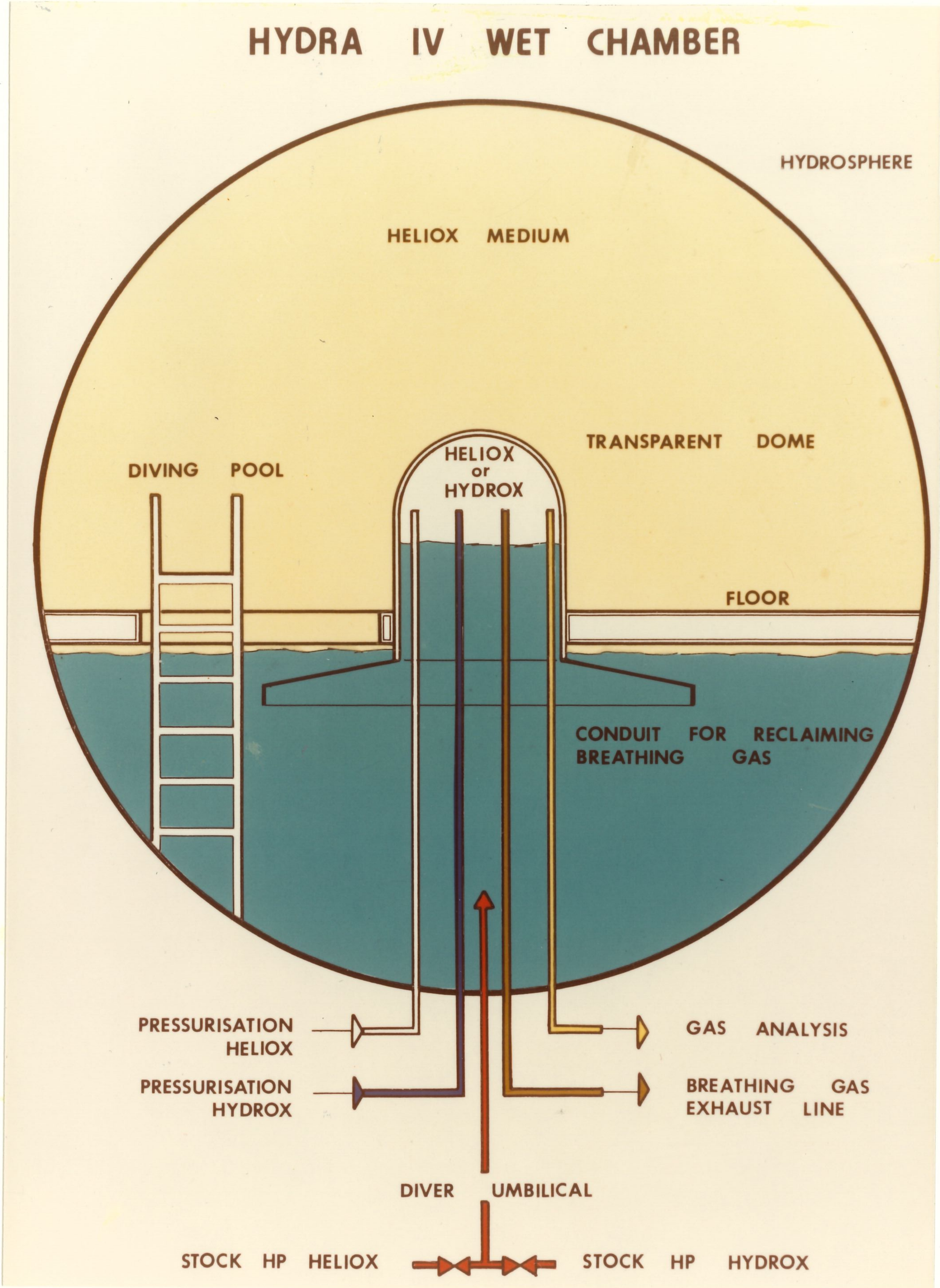

HYDRA IV WET CHAMBER
HYDROSPHERE
HELIOX MEDIUM
TRANSPARENT DOME
DIVING POOL
HELIOX
or
HYDROX
FLOOR
CONDUIT FOR RECLAIMING
BREATHING GAS
PRESSURISATION
HELIOX
GAS ANALYSIS
PRESSURISATION
HYDROX
BREATHING GAS
EXHAUST LINE
DIVER UMBILICAL
STOCK HP HELIOX
STOCK HP HYDROX

FIGURE 1

The hydrox mixture was prepared at COMEX with the assistance of AIR LIQUIDE.

At 300 metres, because of the narcotic effect of the hydrox mixture with 2 % oxygen, already quite noticeable at 240 m depth, it was decided to try a trimix of hydrogen, helium and oxygen.

Two different compositions were prepared and tested at 300 metres :

- H_2 - He - O_2 (74/24/2)
- H_2 - He - O_2 (59/39/2)

with a precision of 1 %.

The PH_2 of these mixtures were equivalent to :

- 224 m of hydrox 98/2 for the 74/24/2, i.e. 22.94 bar
- 187 m of hydrox 98/2 for the 59/39/2, i.e. 18.29 bar

- During the tests under the dome at 120 metres' pressure depth the CO_2 was scrubbed and the PIO_2 maintained by continuous ventilation of the atmosphere inside with heliox or hydrox.
  At 180 metres and below, as the PIO_2 was sufficiently high, it was only necessary to scrub the CO_2. This was done by putting soda lime into the dome and changing it every day.

- Comparative heliox/air tests were carried out during decompression at pressure depth of 80 metres using :

  - air with 21 % O_2
  - heliox with 20 % O_2.

METHODS

1 - COMPRESSION

Compression to 300 metres was gradual with stops at 120, 180, and 240 metres.

Tests were carried out in the dry and in the wet at each stop with the divers breathing hydrox.

* Compression rates

0 - 150 metres	=	3 metres per minute
150 - 200 metres	=	1 metre per minute
200 - 300 metres	=	0.33 metre per minute

* Compression time

0 - 120 metres	=	40 minutes
120 - 180 metres	=	40 minutes
180 - 240 metres	=	2 hours 20 minutes
240 - 300 metres	=	3 hours

* Stop time

at 120 metres : 14 hours 20 minutes
(November 14th from 0840 to 2300 hours)

at 180 metres : 40 hours 20 minutes
(from November 14th at 2340 hours to November 16th at 2200 hours)

at 240 metres : 46 hours 40 minutes
(from November 17th at 0020 hours to November 18th at 2200 hours)

* Bottom time at 300 metres

64 hours (from November 19th at 0100 hours to November 21st at 1700 hours).

* Prior to compression the hyperbaric chambers were flushed out with heliox to remove any trace of nitrogen.
The PIO_2 was maintained at 400 mbar throughout compression and bottom time.

2 - DECOMPRESSION

Decompression from the 300 metre bottom depth did not follow the conventional profile because there were two stops :
- one at 150 metres for longer hydrox exposure tests,
- one at 80 metres for comparison tests with air narcosis.

* Decompression rates

300 - 200 metres	=	0.025	metre/minute	(or 40 minutes per metre)
200 - 15 metres	=	0.022	metre/minute	(or 45 minutes per metre)
15 - 0 metre	=	0.0167	metre/minute	(or 60 minutes per metre)

* PIO_2

- from 300 to 200 metres : PIO_2 = 0.6 bar
- from 200 to 10 metres : PIO_2 = 0.5 bar
- from 10 to 0 metre : O_2 = 21 %

At 10 metres the chambers were flushed out with air.

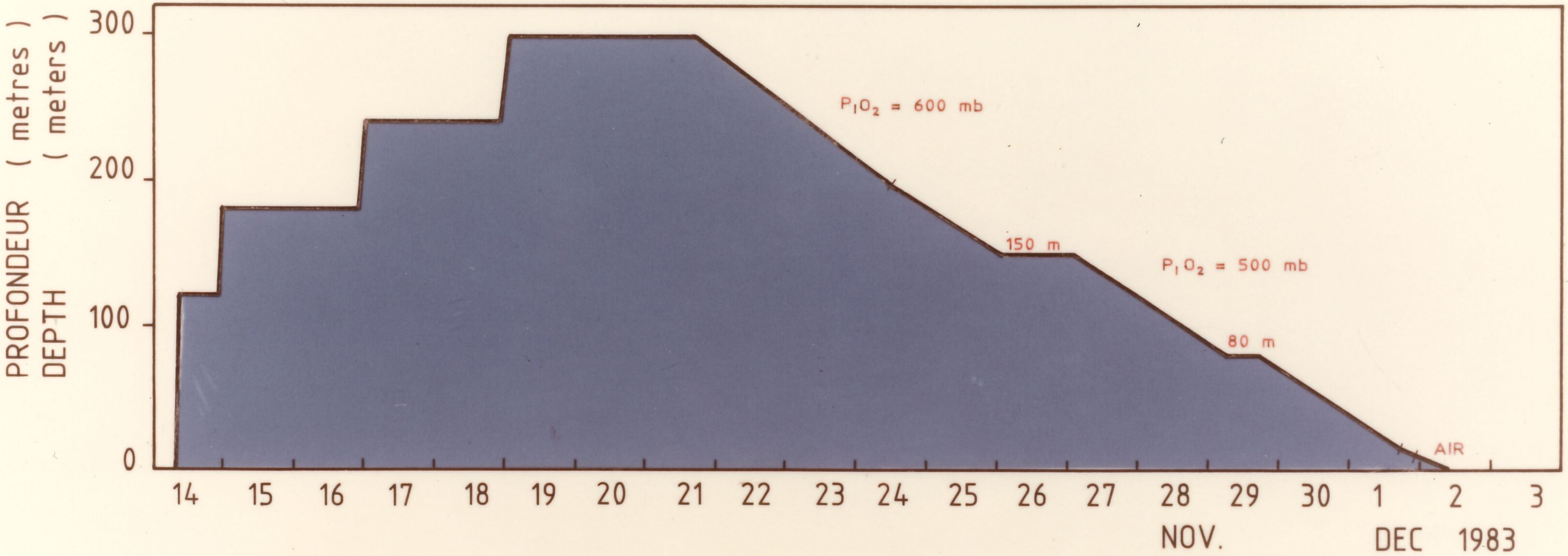
* 150-metre stop

This stop was made on November 26th for 25 hours 20 minutes.
Three of the divers were on hydrox for periods of 2, 4 and 6 hours.

* 80-metre stop

The stop was made on November 29th for 10 hours 30 minutes in order to make a comparative study of nitrogen narcosis at 80 metres on the same subjects and in the same conditions as for hydrogen.

Decompression began at 1700 hours on November 21st and ended at 1100 hours on December 2nd, 1983.



HYDRA IV 1983

3 - DRY TEST PROTOCOL

The diver enters the little dome, sits down on the seat ; the lower part of his body is under water. The first series of tests is carried out in first a heliox medium and then a hydrox medium. The tests are identical in both cases and the sequence is as follows :

- Period of "Impregnation" on adaptation to medium	10 min.
- Manual dexterity test (MD) 1 hand	2 min.
- Visual choice reaction time test (VCRT)	2 min. 30
- Multiplication test	2 min.
- Number similarities test	2 min.
- Electroencephalogram (EEG)	8 - 10 min.
Time allotted	30 min.

After returning to the heliox atmosphere of the living chamber, the divers were submitted to ultrasonic detection of circulating bubbles for 4 to 6 hours (CERTSM).

4 - WET TEST PROTOCOL

The diver is completely equipped for underwater work. He goes into the water and comes up under the dome, which is now filled with water. He breathes heliox for the first half hour of the test and hydrox for the next hour. The test schedule is as follows :

On HELIOX	- Adaptation period	10 min.
	- VCRT	2 min. 30
	- Cyclorower	7 min.
	- Rest period	5 min.
	Time allotted	25 min.
On HYDROX	- Adaptation period	10 min.
	- VCRT	2 min. 30
	- Cyclorower	7 min.
	- Rest period	5 min.
	- Puzzle	0 to 30 min.
	- VCRT	2 min.
	Time allotted	30 to 60 min.

On HELIOX - Diver leaves the water
- Undergoes Doppler circulating bubble detection for 4 to 6 hours.

During this underwater tests the divers are monitored for :

- ECG
- ventilation
- respiratory P

5 - LONG-TERM EXPOSURE PROTOCOL

At 150 metres three of the divers were exposed to longer periods on hydrox of 2, 4 and 6 hours. During this prolonged exposure to hydrox the manual dexterity (MD), multiplication and number similarities tests as well as the EEG were repeated at regular intervals in the dry, under the dome. Only the VCRT could not be correctly carried out. Complete blood tests were made before exposure, upon leaving the dome and six hours after the end of the prolonged hydrox exposure.

M. GIRAUD DOING THE MULTIPLICATION TEST
UNDER THE DOME IN HYDROX 98/2

R E S U L T S

SCHEDULE AND SUMMARY OF THE OPERATION

Monday, November 14 : Starting at 0800 hours the divers were compressed to 120 metres. During the day tests were carried out on hydrox in the dome set up in the middle of the hydrosphere, at this level. First use of the 98/2 hydrogen atmosphere reassuring. Further compression of 60 m during the night.

Tuesday, November 15 and Wednesday the 16th : 180 metres. Teams A and B go alternately into the pool and under the dome for comparison tests on heliox and hydrox. Three of the six divers felt a slight narcosis but all six observed greater respiratory ease on hydrox. Further compression of 60 metres during the night of November 16-17.

Thursday and Friday, November 17 and 18 : Depth 240 metres. Same procedure of alternate tests for Teams A and B. All divers experience hydrogen narcosis and two of the six consider it acceptable. All agree pulmonary ventilation greatly improved and muscular fatigue much reduced on hydrox. Compression 60 m during the night of November 18-19.

Saturday and Sunday, November 19 and 20 : Depth 300 metres. The composition of the breathing mixture has been changed by adding 24 % helium (74/24/2). During the tests in the gas media and under water the divers experience a medium degree of narcosis, which four of them have little difficulty controlling, and still the incomparable ergonomic comfort.

Monday, November 21 : Still at 300 metres. The two professional lead divers undergo tests in the water with a trimix containing only 59 % H_2. Same ease of ventilation and barely perceptible narcosis. During the evening decompression begins.

Saturday, November 26 : Depth 150 metres. Three divers are exposed to hydrox 98/2 under the dome for 2, 4 and 6 hours. No narcosis. The second, Marcel GIRAUD, is the first person ever to have eaten a complete meal in a hydrogen atmosphere.

Upon returning to heliox he proved to have a fairly high number of isobaric counterdiffusion bubbles, with no pathological consequences. Blood tests of the three divers did not reveal any biological changes. Decompression resumes at 0100 hours, November 27th.

Tuesday, November 29 : Depth 80 metres. Four divers are exposed to heliox 80/20 and then to air, under the dome. The other two undergo the same test in the water. Nitrogen narcosis is spectacular and uncontrollable in three divers out of six. Decompression resumes at 1950 hours.

Friday, December 2 : At 1100 hours the divers come out of the chamber.

Operation HYDRA IV has gone off well from the point of view of safety, of overall organization and of the divers' schedule.
The only problem was communications, which were often poor due to faulty equipment or an unscrambler not suited for hydrox use.
The hydrogen narcosis phenomena which gradually appeared were able to be evaluated for the first time and the PH_2 increase controlled at 300 m by using a new trimix. The experiment shed light on a number of questions which had remained unanswered for many years concerning the practical use of hydrogen in deep diving.

SUBJECTIVE RESULTS

1 - FATIGUE INVESTIGATION

All the six divers evaluated their state of fatigue during the time they were in the chamber as being between **fairly good condition** and **in tiptop shape.**

- They slept **well** or **fairly well** with a few exceptions : diver A2's sleep was disturbed during the nights of compression and some of the divers relived in dreams or nightmares the activities of the day.
- Their appetites were **good** and they ate well.
- Some pains in the joints were reported during compression (wrists, shoulders and knees), with cracking of the joints during movement.
- Two divers suffered from otitis externa, with which caisson divers are all familiar, and which was treated in the usual way (POLYDEXA).

2 - HYDROGEN EFFECT

On the breathing mixture the PH_2 was 18 bar at 180 m, 24.5 bar at 240 m and 23 bar at 300 m (trimix).

As the main point of the HYDRA IV project was to study the narcotic potency of hydrogen, the self-observation reports of each of the six divers breathing this gas at pressures of as much as 24.5 bar, are of great importance. These have been published in a more detailed study elsewhere, but their reactions can be summed up as follows :

Diver A1 : strange but scarcely noticeable hydrogen effect at 180 m. More pronounced but not very disturbing at 240 and 300 m.

Diver A2 : Pronounced hydrogen effect at 180 m ; more severe at 240 m with soporific narcosis leading to sleep.

Diver A3 : Unpleasant narcosis difficult to bear at 240 m.

Diver B1 : Slight narcosis at 180 and 300 m ; annoying at 240 m.

Diver B2 : Hydrogen effect scarcely felt even at 240 m.

Diver B3 : Slight narcosis at 180 and 300 m : more pronounced but pleasant at 240 m.

PSYCHOMETRIC TEST RESULTS

The complete individual results of the psychometric tests are contained in the main HYDRA IV Report.

1 - MANUAL DEXTERITY

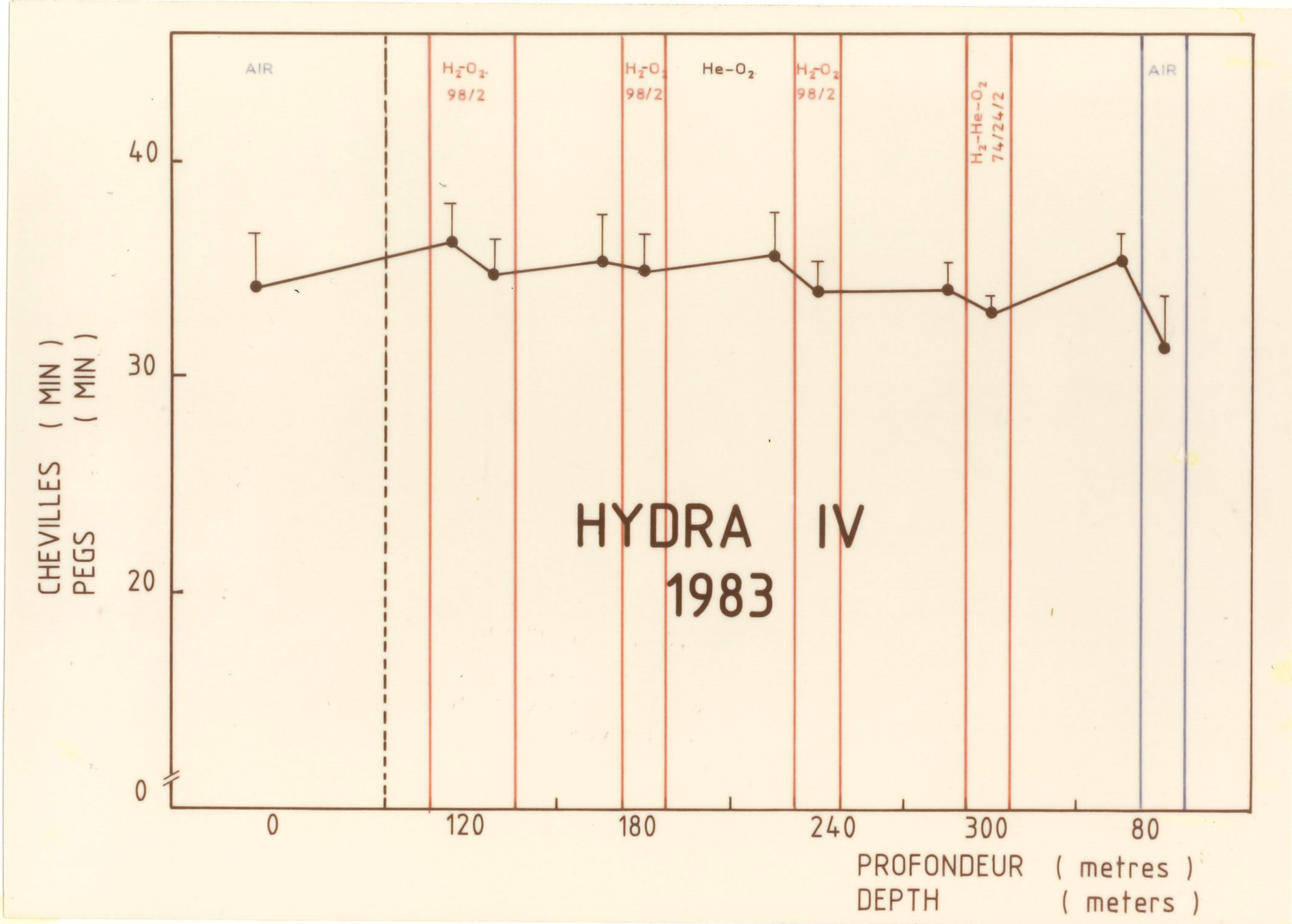
The curve representing the mean evolution in performance during the course of the entire experiment is shown in Photo 1.
There is little variation, the MD values remaining between 33 and 36 pegs inserted per minute, except for minor deterioration of little significance, from heliox to hydrox, at 240 and 300 m (- 4.5 % and - 3.1 %, respectively, on the average).
The percentages of variation between heliox and hydrox at the same depth are not very great and are erratic, depending on the subject. In one subject (A2) there is a systematic deterioration of MD on hydrox at all depths.
The drop in performance level between tests on heliox 80/20 and on air at 80 m, on the other hand,is more pronounced, - 11.6 % on the average.
There is also a slight drop in performance at 300 m on heliox compared to the preceding depths of 180 and 240 m on heliox.

2 - VISUAL CHOICE REACTION TIME : VCRT

This test was carried out as part of the series performed in the dry under the dome and in the wet under water.

Many of the values from 300 m on are missing because of equipment failure.
The rather considerable standard deviation (i.e. individual differences) render the VCRT modifications quite minor and of little significance.

The increase in VCRT at 240 m is largely due to one diver (A3) whose VCRT performance deteriorated with the increase in depth. Hydrox did not alter the VCRT either in the dry or the wet.



CURVE REPRESENTING THE MANUAL DEXTERITY MEAN AND STANDARD DEVIATION FOR SIX DIVERS DURING THE COURSE OF HYDRA IV AS A FUNCTION OF DEPTH AND BREATHING MIXTURE.

PHOTO 1

3 - MULTIPLICATION TESTS

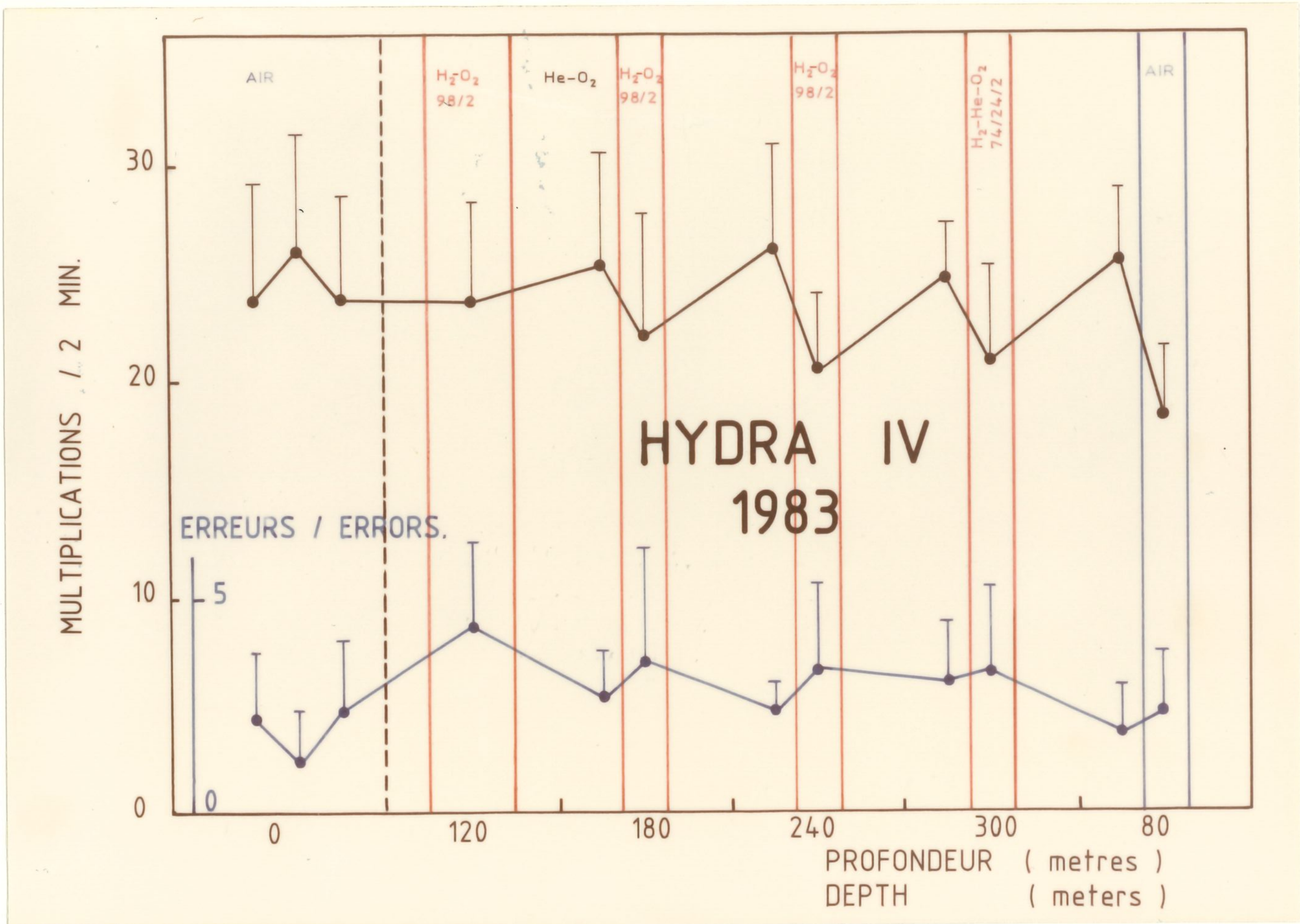
The mean evolution of their overall performance (6 divers' scores ± Sd) is given in Photo 2.
The mean curve shows that for 180, 240 and 300 m there was a deterioration in performance on hydrox compared to the reference gas, heliox, at the same depths, with an increase in the number of errors. The mean percentage of deterioration at 180 m from heliox to hydrox is - 13.8 %, becoming - 19.6 % at 240 m and - 15.1 % at 300 m on a trimix with 74 % H_2 equivalent to hydrox 98/2 at 224 meters.
Thus the degree of deterioration shown by this test would appear to be proportional to the partial pressure of H_2. But the performance drop from heliox to hydrox is still less than the drop observed at 80 m between heliox 80/20 and air (- 28.4 %).

4 - NUMBER SIMILARITIES TEST : NS

The mean curve, represented in Photo 3, shows fairly great individual variations which tend to render the drop in NS from heliox to hydrox at 180, 240 and 300 m of little significance. The tendency is quite clear, however : the performances are not as good on hydrox.
The mean variations are clear, although moderate : - 4.4 % at 180 m, - 6.4 % at 240 m and - 8.7 % at 300 m on trimix 74/24/2. For this test the performance is not proportional to the PH_2 (little variation). At 80 m on air the mean deterioration was - 12.6 %.

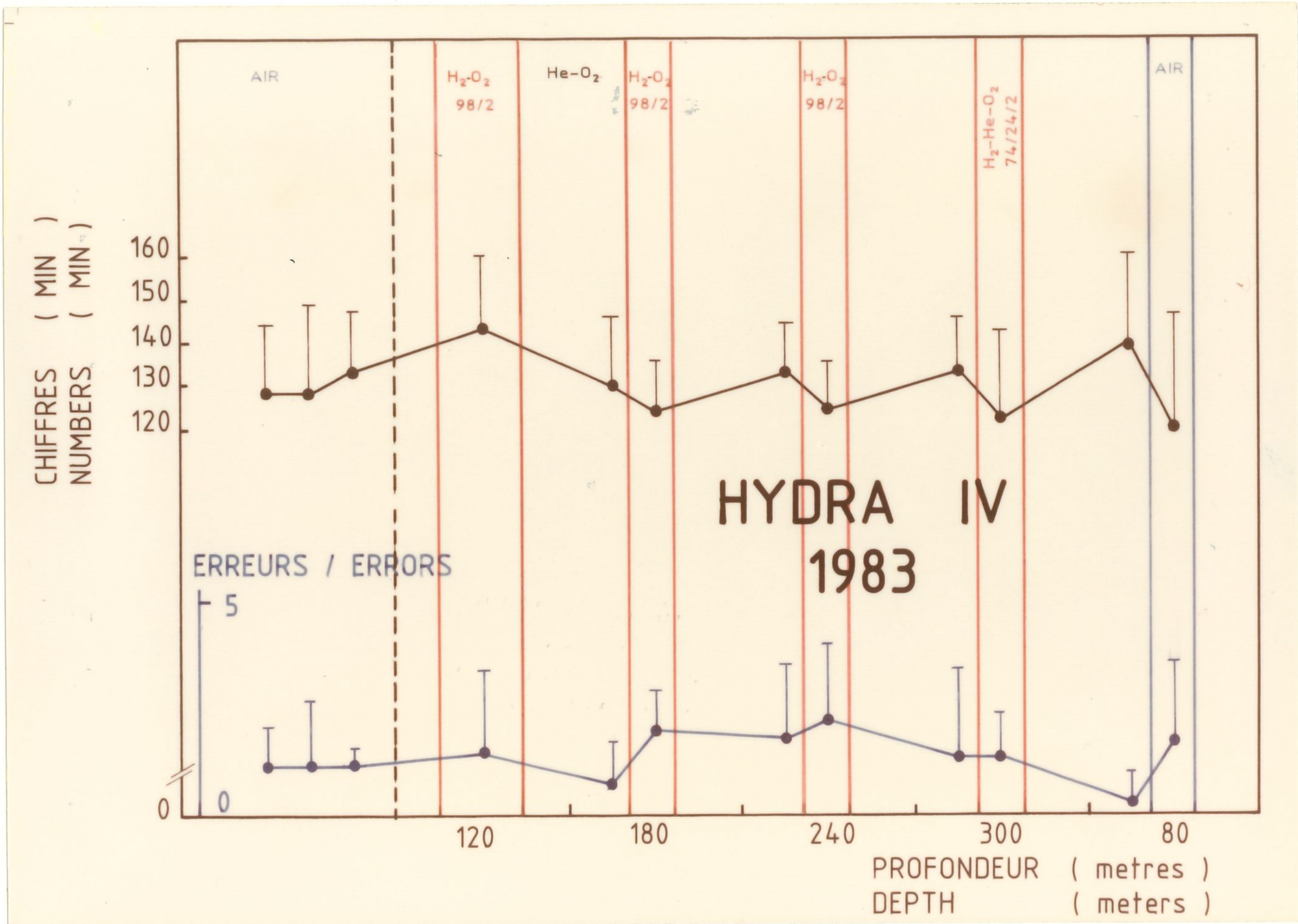
5 - TESTS DURING LONG-TERM EXPOSURES AT 150 M

The psychometric tests (MD, multiplication problems and NS) were given to three divers who undertook long-term exposure to hydrox at 150 meters : 2 hours (diver B2), 4 hours (diver A1) and 6 hours (diver B1) respectively. The tests were taken several times by the same diver during the exposure period.



CURVE REPRESENTING THE MEAN PERFORMANCE OF THE 6 DIVERS ON THE MULTIPLICATION TEST AS A FUNCTION OF DEPTH AND BREATHING MIXTURE.

PHOTO 2



CURVE REPRESENTING THE MEAN PERFORMANCE OF THE 6 DIVERS ON THE NUMBER SIMILARITIES TEST AS A FUNCTION OF DEPTH AND BREATHING GAS.

PHOTO 3

There is no deterioration in performance during the time spent on hydrox :

- For MD : the performances remained close to a mean value with no particular tendency toward improvement or degradation (except for the last high-score test of diver B1 who apparently was glad to get the test over with !).

- The multiplication tests do not show any falling off of performance except in the case of diver B1 who was under the dome for 6 hours. But this lag was due to failing motivation, no doubt, since the last test score approaches that of the reference test in heliox.

- The NS test results are stable for B1 but A1 and B2 increased the number of problems completed (B2 also increased the number of errors). It was observed that this diver B2 adapted differently to the experimental conditions, increasing his speed but making more mistakes.

BIOLOGICAL RESULTS

The blood and urine samples taken before and after prolonged exposure to hydrox at 150 meters of three divers were analyzed by the MONTGRAND medical analysis laboratory.

Samples were taken twice prior to exposure, the 25th of November during decompression (around 170 m) and the 26th of November at the 150 m stop. After exposure samples were taken immediately following exposure and again 6 hours later.

The results of urinalysis (Na^+, K^+, Cl^-, urea, creatinine, Ca^{++}, phosphorus, uric acid, pH) were completely normal but not directly comparable as the fractional diuresis was not very well achieved by the divers.

The results of blood analysis are normal. The minor variations between the two post-dive samples in the blood cells are negligible, equivalent to or less than the variations in the two control samples. The study of certain coagulation factors (cephalin kaolin time, prothrombin index, thrombelastograph curve and fibremia) did not reveal any significant variations following hydrox exposure. The same is true for the blood biochemistry and the serous enzymes .

The blood and urine analyses made before and after the HYDRA IV dive will be published at a later date.

DISCUSSION

SUBJECTIVE ASPECTS OF HYDROGEN NARCOSIS

As has been seen in the divers' self-observation reports, there is definitely a "hydrogen effect" which can be assimilated to narcosis, i.e. to the psychotropic action of gas at pressures higher than atmospheric pressure. This narcosis, at least down to 240 m (with a PH_2 of 24.5 bar at an absolute P of 25 bar), does not appear to affect behavior (with the exception of diver A2 falling asleep, or 1 case out of 6 subjects and 12 exposures). It is objectively confirmed, on the other hand, by the general deterioration observed in the psychometric tests. We should like to make the following comments concerning the subjective aspects :

1 - IMPORTANT DIFFERENCES BETWEEN INDIVIDUALS

Two fo the divers, A2 and A3, proved to be highly sensitive compared to the four others, of whom two (divers A1 and B2) were very little sensitive. Which meant the results were rather dispersed.

2 - NOVELTY OF THE EXPERIMENT

Never before had anyone breathed hydrox beyond 160 meters (ZETTERSTROM, 1945), thus the divers were in a novel situation which could very well comprise certain unknowns, and they might quite legitimately experience what we will call the qualms of the pioneer. This emotional component, which had already been perceived but was not very sensitive in the HPNS, is necessarily much moreso in psychic states troubled by a psychotropic drug.

In addition, the more aware the divers were that the experiment was centered on the narcotic effect of hydrogen, the more they felt responsible for detecting and describing it, the more they watched themselves to discover the slightest unusual sensation. Which explains the minor signs reported at 120 meters whereas later on, at the 150-meter decompression stop when the experiment was nearly over, the three divers who went back on hydrox did not feel anything unusual at all. All of this must be taken into account when interpreting the introspective data.

3 - THE SPECIFIC CHARACTER OF HYDROGEN NARCOSIS OR HYDROX EFFECT OR THE HALLUCINANT POWER OF HYDROGEN

We can take our choice. But we are inclined to favor the term narcosis adopted by the Anglo-Saxons for nitrogen narcosis. For it is indeed the narcotic potency of the gas which became manifest, as with nitrogen, protoxide of nitrogen and most of the anesthetic gases, and it is especially in the evolution that the danger exists.

But before the narcosis stage a hallucinatory syndrome develops which is more or less apparent and varies with the individual, the depth and the hydrogen pressure. Essentially this has two aspects, viz. :

1°/ In a vigilant, active person there are both sensitive and sensory changes :

- tactile hypoesthesia, even hypoalgesia (the face can stand the overtight mask it could not stand in heliox)
- pleasant warm flush diffused throughout the body persists on hydrox, disappears on heliox
- alteration of sense of taste (and perhaps of smell)
- sharper vision, colors more luminous and orangey
- hyperacusia, as though external sounds were closer and more distinct.

These aberrations, howbeit slight down to 240 meters, are more or less well accepted by the diver but do not appear to impair his lucidity.

2°/ If the subject is awake-at-rest with his eyes closed, interoceptive hallucinations begin to take over, with distortion of the body scheme, spatial disorientation, the impression of losing one's balance and a distressing sense of isolation. Mental activity takes the form of a "closed-circuit dialogue". If isolation is prolonged, after a period of time which varies with the person, there is a tendency toward drowsiness which was perceived by two of the divers and became very nearly an objective reality with one of the two.

4 - DIFFERENCES BETWEEN NITROGEN NARCOSIS AND HYDROGEN NARCOSIS

All of the comparisons do not agree, all of the preferences do not go to one more than to the other. The majority reported the following :

a) when the gas is changed, hydrogen narcosis sets in more slowly and disappears more slowly than nitrogen narcosis

b) hydrogen narcosis is more hallucinatory and less ebrious than nitrogen narcosis

c) at critical pressure alteration of the mental process is more pronounced on nitrogen than on hydrogen ; this seems to be confirmed by the psychometric tests the divers took (see test results). At the same degree of narcosis - and this "same degree" has yet to be defined ! the professional divers consider hydrogen to be less incapacitating than nitrogen.

d) finally, it would appear that the subject "under the influence of hydrogen" is more aware of his condition than when "under the influence of nitrogen". All six divers agreed that they felt :

- a sensation of insecurity on hydrox
- a false sensation of security on nitrogen

But after all, isn't the familiar and the routine exaggeratedly reassuring and doesn't the unfamiliar and the novel always have a disquieting aspect ?

EFFECT OF HYDROGEN ON THE PSYCHOMETRIC TESTS

The psychometric tests were used to study qualitatively and quantitatively the narcosis induced by hydrogen.

- the manual dexterity test measures the rapidity and precision of a simple movement of the hand and fingers.
- the visual choice reaction time test assesses the rapidity of decision-taking and action controlled by a light signal.
- the multiplication test measures the ability to make use of a simple acquired intellectual mechanism and the immediate memory.
- the number similarities test measures alertness and the capacity for instantaneous observation.

The intellectual tests were administered several times before the divers went into saturation in order to minimize confusion between test practice and the deterioration in performance we expected. Thus the divers had more or less attained their normal level of performance prior to the heliox / hydrox comparative tests.

- At 120 m on hydrox the scores for the four tests differ little from the scores at the surface.
- At 180 m there is a drop in the scores for multiplication, number similarities and VCRT, but no significant statistical difference between heliox and hydrox (Student t test). The test which was affected the most was the multiplication test although the heliox / hydrox difference was not significant for the Student t ($p < 0.30$) but was significant for the comparison test of the differences with 0 ($p < 0.01$) used for the paired series.
- At 240 m, a depth at which all of the divers experienced narcosis in varying degrees, the multiplication test scores dropped nearly 20 % whereas the other test scores were modified much less : - 6 % for number similarities, - 4.5 % for manual dexterity and - 2 % for the VCRT. The heliox / hydrox difference for the multiplication test has only a probable significance ($p < 0.05$ by Student t) and no significance by the paired series test.
- At 300 m the PH_2 in the breathing mixture was less than that of the hydrox used at 240 m, and the drop in overall performance on the multiplication test is less pronounced, - 15 %. The number similarities test is affected more than at 240 m, however, - 9 %, but the difference is not significant. The VCRT and MD show virtually no variation.

By comparison, the same tests were administered on air at 80 m and the results show that nitrogen narcosis at this depth is much more pronounced than hydrogen narcosis at 240 m, viz. :

- – 11.6 % for MD, probably significant ($P < 0.05$ by the Student t)
- – 28.4 % for multiplication, a significant difference ($p < 0.01$ by the Student t)
- – 12.6 % for number similarities, difference not significant ($p < 0.20$ by Student t test)

Furthermore, all of the tests were disturbed on air at 80 m, whereas hydrogen only seems to have affected the two intellectual tests.

Table 1 compares the results of the tests at 240 m and 300 m on hydrox and at 80 m on air relative to the test scores on heliox :

Table 1

Mean variation in performance	at 240 m on hydrox 98/2	at 300 m on trimix 74/24/2	at 80 m on air
Manual dexterity	– 4.5 %	– 3.1 %	– 11.6 %
VCRT in the dry	– 2.2 %	+ 0.1 %	–
Multiplication	– 19.6 %	– 15.1 %	– 28.4 %
Number similarities	– 6.4 %	– 8.7 %	– 12.6 %

The tests administered on air at 80 m in the same conditions (under the dome, with heliox reference tests at the same depth) afforded a good basis of comparison for the test series. This was particularly desirable since the results published in the available literature on the quantitative evaluation of air narcosis are rarely comparable among themselves (the tests vary somewhat, or the diving conditions do, such as PH_2, depth, compression speed, exposure time, etc.). BENNETT and BLENKARN (1974) studied air narcosis at 87 m by comparing tests taken on heliox 80/20 and on air at that depth. They recorded a reduction of – 29.8 % in the arithmetic test scores, which approximates our own observations. Other authors have only found a drop, in air dives, relative to surface results, of : – 13 % at 91 m (SCHREINER et al., 1972) ; – 18 % at 80 m (ADOLFSON, 1967).

In our conditions the difference in the arithmetic test scores between the surface and 80 m on air is around 25 %.

Manual dexterity tests are chiefly used for studying HPNS but some scientists (BENNETT and ELLIOTT, 1982 ; MARTIN-CHAVE, 1983) have used them for studying air narcosis. Our MD test helped to show up the difference between the nitrogen effect and the hydrogen effect. Judging from the test results and the divers' observations, it would appear, therefore, that air narcosis and hydrogen narcosis take different forms. Hydrogen affects the intellectual faculties, namely the ability to make use of simple acquired mechanisms, without modifying either the rapidity or the precision of an elementary movement, or the VCRT. The effect of hydrogen greatly resembles the effects of hallucinant drugs, with hallucinations, dysesthesia, impression of interior dialogue, alteration in body scheme, etc.

The two types of narcosis are thus not directly comparable, but we can nevertheless assess the narcotic potency of H_2 compared to air for **a given test.**

The narcotic potency of H_2 for the multiplication test was about 21 % that of nitrogen. For the number similarities test it was only 15 % that of nitrogen. These values, admittedly theoretical, can serve as a basis for establishing a tentative depth limit for the use of hydrox 98/2. Assuming 50 meters as being the safe limit for air, in accordance with British standards, the safe limit for hydrox would probably be around 200 meters. But this limit is only based on the results of the tests we used, which according to the divers did not reveal certain hallucinatory effects of hydrogen. Other tests must therefore be used in future experiments with this gas in order better to assess quantitatively all of its effects.

UNDERWATER EXERTION ON HYDROX

The chief interest in the use of a hydrogen-based breathing mixture rather than heliox lies in the advantage it offers ragarding density of the mixture to be ventilated and consequently greater facility of breathing with a concomitant reduction of exertion while working. It was this second consequence that we studied by monitoring HR during the dives, both awake-at-rest and during the exercise periods on the cyclorower. Table 2 shows the values of the different breathing gas densities used under water at 120, 180, 240, 300 and 80 meters' pressure depths.

Table 2 ("wet" gas at 37°C - 98.6°F)

DEPTH / GAS MIX	120 m	180 m	240 m	300 m	80 m
Heliox 98/2	2.32 g/l	3.40 g/l	4.43 g/l	5.43 g/l	-
Hydrox 98/2	1.33 g/l	1.96 g/l	2.52 g/l	-	-
Hydrox 74/24/2	-	-	-	3.66 g/l	-
Hydrox 59/39/2	-	-	-	3.97 g/l	-
Heliox 80/20	-	-	-	-	3.39 g/l
Air	-	-	-	-	10.27 g/l

The HR results showed :

- no excessive tachycardia during kitting up
- HR stable during heliox dives but slightly high
- exercise on the cyclorower did not give rise to significant tachycardia (HR < 120 beats/min) but the exertion did not exceed 35 watt.
- the HR recorded during hydrox dives were always lower than those on heliox. This would seem to suggest a reduced breathing effort on hydrox which facilitates the diver's work and recovery, with a beneficial effect on the heart rhythm.

Our experiment was not sufficiently rigorous, however, to substantiate this hypothesis conclusively, because the dives always began with heliox. It would have been interesting to reverse the order, a procedure which had not been scheduled, as the HR seems to decrease gradually during dive time even without changing gas.
This came out during the course of the ENTEX 9 experiment (COMEX Report 1984), where continuous HR recording using the Holter method of a diver at a pressure depth of 570 m showed a slow decrease in his heart rate during one hour's dive time.
Our results may, therefore, be nullified by the notion of underwater time, particularly since during the two dives at 80 m on heliox 80/20 and on air the HR decreased with dive time in spite of the considerable increase in the density of the breathing gas (air).

- no change in the ECG tracing on hydrox, even during prolonged exposure in the dry.

Under the conditions of this experiment hydrox did not show evidence of having a pathogenic effect on the heart. It may have a bradycardiac effect, but this remains to be demonstrated.

HYDROGEN TOXICOLOGY

An earlier experiment involving mice (HYDRA III mice, 1984) showed that prolonged exposure to hydrox (600 m - 40 hours - 40 mice) did not produce any histological modifications (liver, heart, kidneys and lungs).

In HYDRA IV the blood and urine analyses performed before and after the dive did not reveal any changes. All of the blood and urine parameters studied were found to be normal immediately after the end of saturation some 6 days following the last exposures to hydrox. Hydrogen therefore does not produce any irreversible changes.

The samples taken just before and after the long-term exposures to hydrox at 150 m and 6 hours afterward also did not disclose any significant changes in the blood and urine parameters studied.

It would appear, therefore, that hydrox has no effect, even at short term, on these parameters, in our experimental conditions.
It would seem that hydrogen behaves as an inert gas in respect to the cellular metabolism but nevertheless induces a hallucinatory effect, exactly like nitrogen, argon, neon and a number of other gases we call "inert".

NEUROPHYSIOLOGICAL STUDY (J.C. ROSTAIN)

RESULTS

* EEG

EEG modifications were visible in the posterior area for rapid activities. For each diver and each depth studied we observe a decrease in the power of the activities in the alpha frequency band in hydrox compared to heliox. Some of the divers also had microsleep patterns which corresponded to drowsiness during the EEG sessions.
For the slow activities which were dominant in the anterior region there was no significant difference between hydrogen and helium breathing.

There was no variation in EEG activities during respiration of the hydrox at 150 meters, whether the dive time was 2, 4 or 6 hours. However at this depth we did not have a posterior lead for two of the divers, which could explain the lack of variation.

* TREMOR

During this experiment, which had a depth limit of 300 meters and thus did not include a study of the HNPS, the number of tests carried out did not permit us to draw any conclusions regarding the effect of hydrox compared to heliox on tremor. The only test made at 300 meters shows a decrease in tremor in one diver, on hydrox. There was no significant difference in the other divers.

COMMENTS

As the EEG study was not the main objective of this experimental dive, the tracings we took are not sufficiently complete to permit us to make a thorough and rigorous study.
Nevertheless, the decrease in alpha activities seems to be a constant from 120 meters' depth onward, throughout the experiment. This decrease may be explained either by a lower power of concentration on the part of the divers, and greater difficulty in fixing their attention while breathing hydrox, or else by some effect of the mixture itself on the cerebral cortex which could reflect directly or indirectly a state of narcosis.

The hydrogen exposure time, only 30 minutes, was no doubt too short to permit observation of other possible modifications in the frequency bands studied, particularly in theta or delta activity.

The absence of EEG modification during the prolonged exposures at 150 meters could be explained by the moderate depth of the stop and by the absence of posterior derivation. It should be noted, however, that the absence of EEG reference on heliox before breathing hydrox makes it impossible to draw any conclusive inferences.

RESPIRATORY FUNCTION ON HYDROGEN AND HELIUM : A COMPARATIVE APPROACH
(G. IMBERT)

DISCUSSION

Four findings are particularly noteworthy :

- improvement of breathing comfort by hydrogen,
- narcotic potency of hydrogen,
- feeling of thermal comfort on hydrogen,
- relative hypoventilation during muscular exercise.

*Improvement in breathing comfort

This was foreseeable, indeed it was already known since the divers who had tested hydrox in the sea a few months before (HYDRA III) had described it. All that was lacking was confirmation and objective measurement.

The most convincing argument in our estimation is furnished by comparing ventilatory data recorded during the semi-stationary phase of muscular exercise on heliox and on hydrox at 180 m . The gain in terms of $\Delta\dot{V}_E$ is more than 20 percent. This observation is completed and clarified by analyzing mouth barograms which shows that for the same ventilation effort the mean flow rates are 20 percent higher on hydrox than on heliox.

* Narcotic potency

The threshold seems to be around 20 bar (290 psi). The narcotic potency of hydrogen was the object of psychometric and neurophysiological studies during HYDRA IV that are discussed elsewhere. But the respiratory measurements have demonstrated two additional elements :

1) Hydrogen narcosis yields undesirable effects on the control of breathing, quite pronouncedly so at 240 m with a resultant disorganization and depressant effect on the breathing pattern which necessitated stopping inhalation of hydrogen in one case. The phenomenon seemed to be rapidly reversible. This fact tends to preclude the hypothesis of a toxic effect (inhibition of cellular respiration, for examnle) in favor of a narcotic effect as such.

2) Hydrogen narcosis is probably responsible for the lower oxygen consumption on hydrox than on heliox, during the exercise at 240 m. The intoxicated divers did not respect the rhythm called for and furnished an expenditure of energy which was ultimately lower in response to exterior demand. The deficit is measurable and even assumes the value of a narcosis index. It could possibly become a criterion for classifying the narcotic potencies of various breathing mixtures, and its ergonomic significance is quite clear.

* Thermal effect

As the dives were carried out in water at 30°C (86°F), the equipment did not include gas heaters. The gas mixture was inspired at essentially the same temperature at which it left the last reduction stage.

Since hydrogen has a reverse Joule-Thomson effect, this temperature was higher for hydrox than for heliox, as the pressure regulator also acted as a gas heater. The divers did not fail to appreciate this exception to the general rule of the physics of gases.

It remains that on account of its molar specific heat 40 percent higher than that of helium, hydrogen may pose more serious thermal problems than helium if it does not enter the respiratory tract at the right temperature. Precise measurements should be carried out in a variety of thermal environment conditions.

* Relative hypoventilation

From 240 m on, even though the muscular exercises were very moderate, there was a decrease in the expired oxygen pressure from the moment the diver began the activity. Ventilation increased, but slowly, and the increase in oxygen consumption was ensured chiefly by the increase in its pulmorary extraction coefficient. The probable corollary of this is slower elimination, thus retention of carbon dioxide.

The variation in ΔP_{O2} (and therefore in ER_{O2}) are significantly greater on heliox than on hydrox . It would not be prudent to deduce that the determining factor is the density of the breathing mixture.
Another possible (but not exclusive) explanation would be that the intensity of the exercises was greater in heliox than in hydrox.

Such variations, which were constant in all of the subjects, for exercises of moderate intensity and at relatively modest depths, should perhaps be considered in relation to the immersion situation and the use of diving apparatus.

* The question of diving apparatus

Although this question does not bear specifically on the comparison of hydrogen and helium properties, the subject must be covered since it pertains to the conditions in which the measurements were made and consequently, to their significance. In the HYDRA IV experiment, the measurements were not made on divers in a dry chamber, but on complex preparations represented by a submerged diver and the diving mask through which he breathed.

This mask is not only a simple external resistance added to internal ventilatory resistances. Between the diver's thoracopulmonary apparatus and the pneumatic system to which it is hooked up, there exist highly complex interactions.

How can one explain, for example, that to improve his respiratory comfort at a depth of 300 meters the diver will increase the intake (inspiration) resistance of his demand valve ? The result is peak-to-peak variations in the buccal pressure in the neighborhood of 50 mbar, but perhaps also pressure waves whose amplitude at inspiration and expiration is roughly equal. Is this the balance for which the oscillating pump the thoracopulmonary apparatus represents is seeking for maximal efficiency ?

Hence, the question arises wether the resistance of the breathing apparatus external circuitry should be minimal, of matched to increased impedance of divers'airways.

CONCLUSION

The purpose of this study was to make a comparative evaluation of the factors limiting the respiratory function and muscular exertion in divers breathing either a hydrogen-oxygen mixture or a helium-oxygen mixture.
The measurements were carried out under pressure, in water, and in conditions roughly similar to deep diving conditions, albeit very comfortable from the temperature standpoint. Simple reliable methods were used for measuring oxygen consumption, pulmonary ventilation and pressure variations in the divers' mask, i.e., at the junction point between the respiratory tract and the diving gear.

Significant differences appeared at 180 m and 240 m, depths at which the measurements were carried out on 6 divers :

- The advantages of hydrogen are objectively demonstrated in particular by the pulmonary ventilation measurements : with no additional effort the divers obtained higher ventilatory flow rates ;
- The disadvantages are objectively demonstrated in particular by the oxygen consumption, considered as an index of energy expenditure : the narcosis induced by breathing hydrogen reduces the diver's ability to perform an exercise requested of him.

To simplify, we could say that the advantages predominate at 180 metres, but the disadvantages at 240 metres.

The maximum pressure for the use of hydrogen as a breathing gas would therefore seem to be in the neighborhood of 20 bar (290 psi).

Tests at 300 m on a limited number of subjects demonstrate the possibility of using hydrogen in a trimix composed of helium, hydrogen and oxygen. These tests do not permit us to say wether these mixtures offered a definite advantage over helium-oxygen at 300 m, but the combination of hydrogen and helium is of definite interest for future developments in deep diving.

Furthermore, certain observations (such as relative hypoventilation during the course of exercises even of low intensity from 240 m on) bear witness to the need to study the effect of diving equipment on the thoracopulmonary mechanics and on respiratory control.

HYDROGEN ISOBARIC COUNTERDIFFUSION IN MAN DURING A 300 MSW SIMULATED DIVE (G. MASUREL)

Two groups of three divers each were subjected to sequential exposures to hydrogenated mixtures at different times throughout a saturation dive with heliox to 300 msw.

The divers were made to breathe the hydrogenated mixture during a stop either in a dry chamber or in water wearing standard diving equipment.

On their return to heliox environment the divers were checked for circulating bubbles in the precordial area using the Doppler ultrasonic detection method.

As regards exposures to 240 and 300 msw, only two divers exhibited a very limited quantity of bubbles in connection with the isobaric counterdiffusion.

At the 150 msw stop during a four-hour exposure, one diver exhibited grade 3 bubbles (KM code (1)) four hours after his return to heliox. The detected bubble flow continued, gradually decreasing, for more than 8 hours.

To conclude, isobaric counterdiffusion remains relatively moderate under our experimental conditions, but increases with exposure time.

(1) KISMAN K., MASUREL G., GUILLERM R.
Bubble Evaluation Code for Doppler Vetrasonic Decompression Data.
Undersea Biomed. Res. 1 (suppl.), 28, 1978.

SPEECH DISTORTION STUDY (J.C. MALHERBE)

In a synthetic hyperbaric atmosphere human speech is greatly distorted, which makes direct communication between divers, or between divers and those on the surface, impossible. This phenomenon is due to the physical properties of the gas in the vocal passage. In the simple case of spoken sounds this results in a spreading of the representative frequency spectrum toward high frequencies, without marked change in the value of the lowest frequency. The spectrum displacement is a function of the gas used and of its pressure.

The "speech distortion" team of the Lasti de Lannion Laboratory (University of Rennes I) recorded the divers' speech during the HYDRA IV experiment, using a control text which the divers read in air at atmospheric pressure, then in heliox, hydrox and trimix at different pressure levels.

The study project followed three main lines :

a) Use of experimental data to check and improve knowledge of speech distortion and treatment of the particular case of hydrox distortion.

b) Development (on computer) of a theoretical model of the vocal passage, taking into account the breathing mixture and its pressure. This study was based on a model created by the CNET speech group which was only valid for air at atmospheric pressure.

c) Design of an efficient corrective device that would be compact and inexpensive, using new electronic components still in the prototype stage.

CONCLUSIONS

1 - It is all the more gratifying that the experimental simulated dive, HYDRA IV, went off without mishap inasmuch as the experimental gas involved is one that is particularly delicate to handle, owing to its physical properties of diffusion and explosibility. The conditions in which hydrogen is used pose in each instance new problems. In this case the most important ones have been solved.

2 - On the physiological plane, the necessity of switching over to $H_2/He/O_2$ at 300 meters was not unexpected. As a result of BRAUER's research on small mammals the hallucinant effect of hydrogen had been anticipated and we were prepared to cope with it. We shall come back to this point later. The program planned for the experiment was strictly adhered to.

3 - The toxicity of hydrox, slightly acidotic, was not substantiated by the biochemical blood and urine examinations after exposures of from 2 to 6 hours. This confirms the results of much more stringent animal experimentation. Hydrogen appears therefore to behave like an inert gas in respect to the cell structures, while nevertheless acting upon the psychic functions, as does our familiar nitrogen at much lower pressure.

4 - The circumstances of this first physiological approach to the problem did not permit us to make an exhaustive investigation into the respiratory function aspect. And while the divers (especially the professional divers) were able to appreciate the "extraordinary" breathing comfort on hydrox, along with the disappearance of the sensation of fatigue during the cyclorower exercise, the results of the measurements carried out in difficult conditions under water ($\dot{V}_E$ and $\dot{V}_{O2}$) are more delicate to interpret. Be that as it may, the study of the heart rates recorded during exertion tends to indicate a decrease in the cardiac cost of exertion while breathing a hydrogen-base mixture.

5 - Switching the divers from the experimental hydrox gas to the storage gas, heliox, according to studies made by LAMBERTSEN and by D'AOUST, should result in isobaric counter-diffusion (I.C.D.) of the inert gas with the formation of stationary or circulating bubbles. During the course of HYDRA IV the Doppler process and echography confirmed the existence of this mechanism which causes bubbles to form as a function of the exposure time and the PH_2 in the conditions of this experiment the phenomenon did not have pathological consequences, but it would be a good idea to continue checking it in the future. With optimism since, in the future, saturation on binary or ternary hydrogen mixtures, without changing over to helium, will tend to reduce the gravity of I.C.D. problems.

6 - As we have seen, certain aspects of hydrox narcosis are different from air narcosis, at least in the initial phase. However it is possible to assess the difference in intensity of the two phenomena, the hallucinant power of hydrogen being about one-fourth that of nitrogen. But this "hydrogen effect" is neither absolute nor useless, because :

- on the one hand it depends on the ambient pressure, which serves as an antagonist to the narcotic action of the gas. (Thus in three of our subjects a comparative study of the narcotic PH_2 as a function of depth shows that the first increases with the second. Other observations permit us to surmise that a professional diver would be able to tolerate a mixture with 63 % H_2 at 300 m and 50 % H_2 at 450 m with a barely perceptible degree of narcosis).

- on the other hand it would itself tend to prevent the High Pressure Nervous Syndrome, just like nitrogen, which would constitute a definite advantage for dives beyond 300 meters' depth.

All of these matters will be clarified by the next experimental saturation dive to 450 meters, HYDRA V, for the positive results of HYDRA IV are particularly encouraging.

7 - Up until now there were only two types of gas which could be used practically as oxygen diluents in hyperbaric conditions, nitrogen and helium. Now it can be hoped that a third type of gas, hydrogen, will make it possible to push back still further the limits on very deep diving imposed by HPNS and respiratory restrictions.

We should like to express our profound appreciation to the sponsors of HYDRA IV for their financial support

AIR LIQUIDE

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