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Diving at 520 m on hydrogen–helium–oxygen mixed gas from dynamically positioned diving support vessel Orelia

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SYNOPSIS

The current trend for diverless systems in deep water, utilising remotely operated vehicles (ROVs), is progressing to evermore sophisticated techniques. However, Comex SA hold the view that there will always be a need for human intervention by divers if these systems fail. This need will manifest itself in the need for diving companies to have the proven ability to provide the effective diving capability to greater depths than have hitherto been possible. This diving trial (Hydra VIII) was the culmination of a series of shore-based trials utilising a mixed breathing gas of hydrogen, helium and oxygen (Hydreliox). The trial was conducted from DSV Orelia which was designed to Mr John Houlder's specifications and developed in-house. The success of this trial, the deepest working dive carried out at sea, is a major milestone for the diving industry.

INTRODUCTION

For some years Comex Services, Marseille have been researching ways of extending the depth at which divers can work effectively.

A diver's air range is limited to 50 m; thereafter divers breathe mixed gases, usually helium–oxygen (Heliox). However, at greater depths there are two problems which reduce their effectiveness: high pressure nervous syndrome (HPNS) and respiratory difficulty.

HPNS manifests itself in a lack of co-ordination and mental acuity and can be ameliorated by a slow compression to depth.

Respiratory difficulty is caused by an increase in density and viscosity of the gas, which requires greater diver breathing effort. Over a period of time this exhausts the diver, mainly due to his inability to get restful sleep.

In 1983 Houlder Offshore's Uncle John with Comex divers successfully carried out hyperbaric pipeline welding at depths of 300 m. Although the work was successfully completed, the divers suffered from fatigue due to the long period of saturation at this depth.

Captain Jeremy H Puckett, Master Mariner, is a Director of Houlder Offshore Engineering (1987) Ltd. He was Master/Installation Manager of the semi-submersible diving support vessel *Uncle John* from her delivery in 1976, to 1985. He worked on this project liaising with the Department of Transport, Lloyd's Register and Comex on the inerting, electrical safety and operational procedures.

Captain Alan P Bartholomew, Master Mariner, has a Diploma in Safety Management. He joined Houlder Brothers in 1955 and served as Master in general cargo and LPG ships from 1970 to 1981. He transferred to Houlder Offshore in 1981 as Master/Offshore Installations Manager on semi-submersible drilling rigs. From 1985 to 1988 he was the Houlder Offshore Group Safety Officer and was on board the Orelia during the Hydra VIII trials in that capacity.

DIVING GAS MIXTURES

Briefly, in normal atmosphere the partial pressure of oxygen (PO_2) is 210 mbar (millibar). During diving operations the PO_2 is usually kept between 200 and 600 mbar depending on the exposure time. With no O_2 the diver will suffer anoxia; with too little O_2 (below 160 mbar) he will suffer hypoxia; and with too much O_2 he will suffer pulmonary O_2 toxicity, depending on the time of exposure. (High PO_2 can be tolerated for short periods only.) If the PO_2 is 400 mbar, a diver will require 40% O_2 at the surface falling to 10% at a depth of 30 m, 5% at 70 m, 2% at 190 m and 1% at 390 m. Thus as the depth increases, the percentage of O_2 in the breathing gas falls. Helium is usually chosen as the balance as it is non-flammable, light and inert.

To achieve reasonable working periods and to reduce the number of decompressions needed, divers are saturated and kept at the working pressure for considerable periods, living in a chamber kept at the working depth and descending to work in a diving bell. Thus they only need to be decompressed at the end of their duty period and not after each dive. Typically a diver spends 3 weeks in a chamber of which decompression takes roughly 1 h/m from working depth.

Experimentation using hydrogen–helium–oxygen mixed gases

Comex research into ways to go deeper and still work effectively led to a series of experiments using hydrogen (H_2) which is lighter than helium (He). However, to prevent fire or

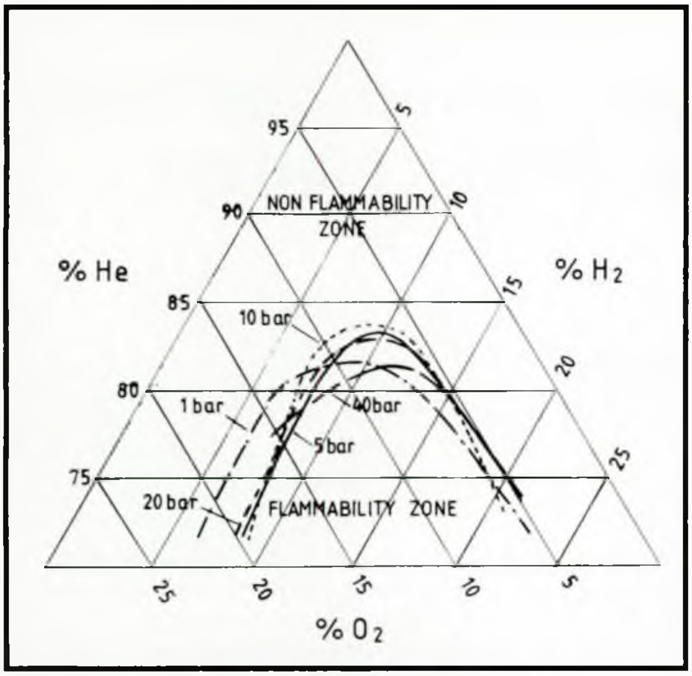

Fig 1: Lower flammability level

explosion, the H_2 cannot be introduced until the O_2 percentage is less than 2% [50% of the lower flammable limit (LFL)]. Experiments were carried out to verify the flammable limits under hyperbaric conditions (Fig 1).

A series of experimental projects (Hydra IV to VII) were conducted in the hyperbaric centre in Marseille.

The final Hydra VIII project was to be a working dive to 520 m carried out at sea from a dynamically positioned diving support system.

PREPARATION OF THE DSV ORELIA FOR WORK

Houlder's Orelia was awarded the contract, hence a scope of work needed to be established in order to identify the hazards and devise engineering solutions so that the work could be accomplished safely. Authorities to be satisfied were the Department of Transport, as the trials came within the scope of the merchant shipping (diving operations) regulations (1975), SI 116, and Lloyd's Register with whom she is classed. Also, the vessel's owners and underwriters had to be satisfied that the risk to the vessel and her crew was minimised.

Ventilation

The previous trials had been carried out in the hyperbaric test facility in Marseille where the chambers are housed in a large hangar-like building and the method chosen to reduce the risk of fire from a gas leak was ventilation at three levels.

Normal ventilation, 5 changes/h
Ventilation at detection of H_2, 0.1%, 15 changes/h
Ventilation at detection of H_2, 0.5%, 50 changes/h

These large ventilation rates were relatively easy to achieve on shore with large exhaust fans in the roof, shrouds around the chambers and inlets around the bottom of the building.

Initial studies on the ship showed that because the diving system was in a long narrow compartment situated under 3 m high double deck ballast tanks the installation costs of a ventilation system would be extremely high. There would also be problems in scavenging the area to ensure that the ventilation was uniform throughout the system, in maintaining watertight integrity and in re-evaluation of the vessel's stability after such modification (Fig 2).

Ducted ventilation

It was then thought that if all leakage areas were shrouded and ducted it might be possible to obtain high ventilation rates locally. Further studies of H_2 showed that any leakage would be liable to ignite because the ignition energy for H_2 is very low and the flammable range is large (4–75%), with a minimum O_2 level of 5%. The flame energy is low but the speed of the flame front increases quickly to detonation at higher concentrations. Thus the ducting would have to be purged and be very extensive to cover all possible leakage points.

Inerting with nitrogen

The risk to the vessel and the safety of life were the primary concerns and hence it appeared that the safest step was to inert the chamber area with nitrogen (N_2). No hazard would be present if a loss of diving gas occurred unless there was also a

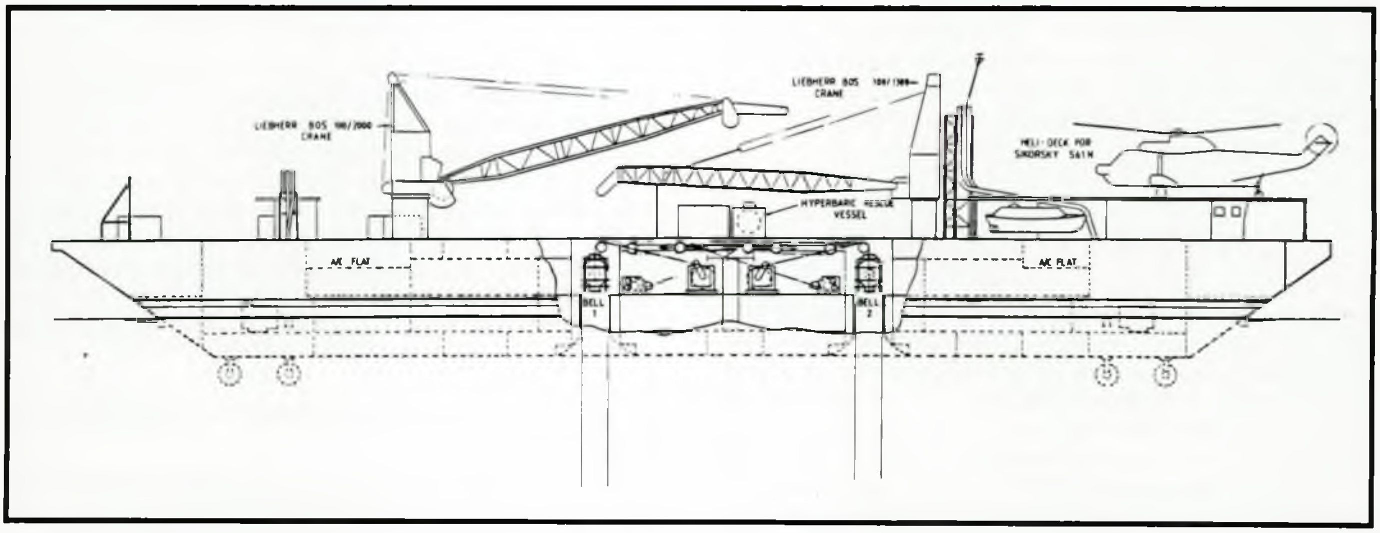

Fig 2: DSV Orelia

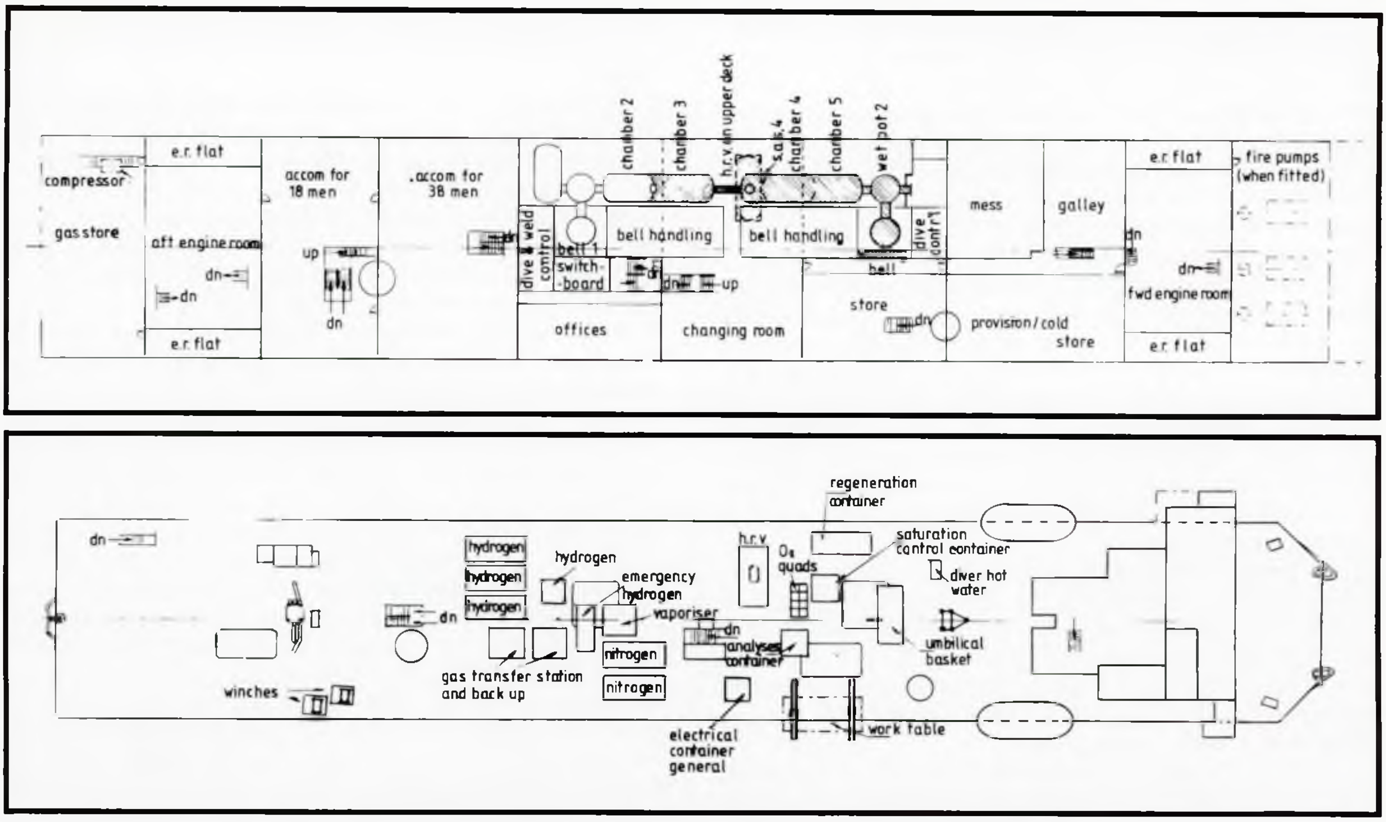

Fig 3: Upper deck (above) and upper tween deck (below) of DSV Orella

leak of O_2 into the space, remembering that the O_2 content of the mixed gas was always less than 2%. This would allow time to rectify the leak and purge the chamber space with N_2. It seemed reasonable to assume that working access to the space whilst inerted could be made safely by personnel who are trained as divers and could be closely controlled. However, standard breathing apparatus exhausts into the atmosphere thus causing local oxygen enrichment and so would be unacceptable as the men would have to go into the space to attend to problems, which could be a leak of diving gas containing hydrogen. Special closed circuit rebreathers had to be evaluated and proved to be suitable. Personnel were trained and operating procedures were written and approved.

Houlder's experience with liquid petroleum gas on ships led us to believe that this was the safest method, and we argued with the Department of Transport and Lloyd's Register on this course of action.

Electrical safety in hazardous areas

In addition to the reduction of hazard it also soon became apparent that if the chamber compartment was considered as Zone 2 the project would be uneconomic due to the large amount of electrical equipment present. The space was then designated as 'Zone 2 special considerations' and the philosophy adopted was to segregate and evaluate the position of electrical equipment which:

1. could be isolated for the duration of the trial when Hydreliox was present.
2. could be isolated on detection of H_2 or O_2 in the space.
3. was required permanently and should be flame-proof.
4. was required permanently and was acceptable even though it was not ex-certified, eg chamber penetrators, etc.
5. could be economically re-sited outside the space.

Having agreed that this was the safest and most economic approach to take the next step was to convince the Department of Transport of the benefits.

Within the industry, government departments have sometimes been accused of being obdurate and so it was with some trepidation that we arranged our first meeting with the Offshore Safety Division of the Department of Transport. We decided that the best approach would be to work very closely with them from the conceptual stage, and it must be said that we found their reactions professional, co-operative and helpful.

The initial meeting divided the work into purely diving aspects (about which the Department needed to be assured were to be conducted within the law as related to the safety of the divers), and the engineering functions (these were considered to ensure that the equipment was fit for the purpose and that hazards to the ship and personnel were at an acceptable level).

The division of hazardous areas had to be arranged so that the only 'below decks' area was the chamber compartment, all others being on the open deck or in the moonpool which was open to the atmosphere (Fig 3).

Modifications on board

All pipework was run on deck, suitably protected from impact. The moonpool's hatch covers were removed so that any leakage within the moonpool or from the submerged bell would dissipate quickly. The winch space adjacent to the moonpools was ventilated at a high rate so that no gas could enter. The original composite bell umbilical was not used as it was uneconomic both to utilise the rotary unions and slip rings in the winch, and to accept the constraints of the hazard in the area. For simplicity, a new umbilical was stored on deck and man-handled via a 2 m diameter, powered umbilical block. It was connected to the hard-piped gas supply on deck. The existing gas regeneration system was disconnected and new self-contained life support units were fitted on deck along with the catalytic decompression unit (CDU) which was used to remove the H_2 and effect the initial decompression. The existing saturation control was only used for Heliox to and from 250 m. Below 250 m, when H_2 was introduced into the system, it was isolated by the internal and external skin valves at the chambers and at saturation control, with the intervening pipework over-pressured with Heliox to prevent leakage into it.

All the penetrations into the inerted space were made either down the moonpool or through high integrity pipework through the double deck tanks. Initially it was thought that the analysers in saturation control could be contained in a fume cupboard bearing in mind the low pressure and flow of sample gas. We were advised, however, that safety could not be guaranteed when using H_2 and a small explosion within the enclosed saturation control would have had disastrous results so the analysers were sited on deck in an open container with the new saturation control panel.

Traditionally diving systems do not utilise remote control valves to any great extent and most diving systems consist of extensive plumbing. This project developed and successfully demonstrated that gas lines could be run directly and controlled from remote panels. Generally development of this technique would significantly reduce the cost and complexity of a diving spread and its mobilisation time.

Access to the saturation chamber is usually through small medical or hand locks set into the chamber side. It was impractical to lock in food etc through these because they were located in the inerted compartment. An existing blanked penetration to the wet pot was used and the 800 mm diameter equipment lock which was previously located in the chamber compartment moved to this penetration where it could be accessed from a safe area by building the equipment lockroom around it. Use of this lock required special procedures to purge the lock with N_2 so that it could be safely brought to atmospheric pressure and opened. Pressurisation was carried out with Heliox for equalisation and transfer to the chamber (Fig 4). The equipment lockroom was fitted with extra exhaust ventilation and gas detection for H_2 and O_2.

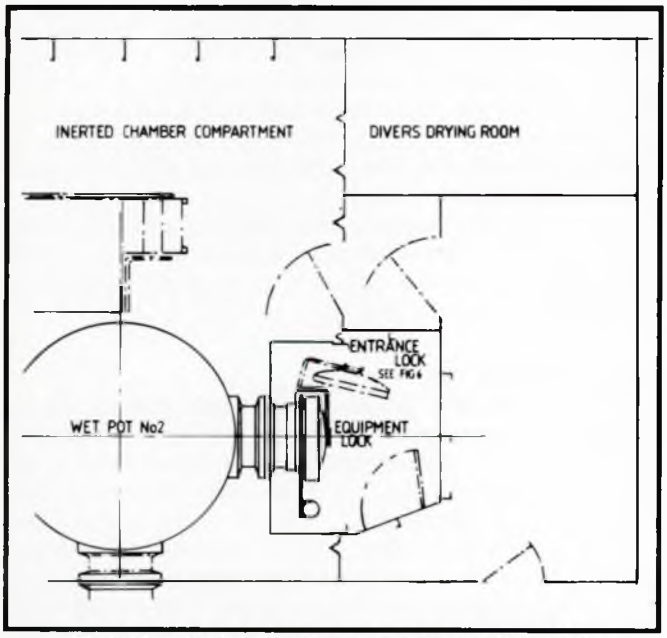

Fig 4: Locks to chamber complex and inerted compartment

Inerting the chamber compartment on the ship (Fig 5)

The initial step was to blank off one of the entry doors which was common to the winch space and fit air locks to the remaining two access points (Fig 6). The concept required the compartment to be maintained slightly above ambient pressure to prevent any ingress of O_2 (35 mbar max), and considerable time had to be taken to ensure that the compartment was airtight as even small leaks from the space would increase the N_2 consumption over the period of the work.

When inerting atmospheric LPG tanks thermal stratification is used to reduce the consumption of N_2. However, the physical shape of the chamber compartment made it unlikely that good stratification would occur. Estimates of N_2 consumption both to achieve and maintain inerting were made and trialed to validate them. N_2 supply for this purpose was from cryogenic liquid gas supplied through vaporisers with demand regulating valves to the chamber compartment where perforated pipes distributed the gas evenly throughout the space.

N_2 stocks on board consisted of liquid N_2 for inerting and high pressure storage for lock operation and vent pipe purging.

Exhaust from the chamber compartment produced during inerting was collected by a perforated pipe run along the deckhead and up the vent, by-passing the water trap relief valve. Obviously some form of pressure relief had to be provided and a water trap was recommended as being the cheapest and most reliable device at such low pressure. This was designed to relieve over-pressure if the N_2 supply regulator failed or in the event of a high pressure gas line leak. The vent tip was about 4 m above the deck. Extensive trials were conducted to prove the system and to arrive at a figure for the quantity of liquid N_2 needed on board for contamination contingencies and daily usage.

Operation

The compartment was inerted to below 3% O_2 and fitted with another catalyser to remove any H_2 leakage. This catalyser was specified to cope with the maximum leakage rate allowed by Lloyd's, 0.5%/12 h (much higher than would ever be tolerated commercially). The catalyser required some O_2 to be present to remove the H_2. If the proportion of H_2 exceeded 2% the catalyser was shut down and a N_2 purge was used to restore the inerted atmosphere.

If the compartment O_2 level was too low a specific volume of air was injected to raise it sufficiently for the H_2 scavenging to work. Water from the catalyser was led overboard via compartment bulkhead isolating valves.

Instrumentation of the chamber compartment

Four Oldham Exd IIc O_2 detectors, 0–25% with alarm levels set at 3%– 4% O_2.

Four Oldham Exd IIc H_2 detectors, 0.1%–2% H_2 in 2% O_2. Alarm levels set at 1% or 2% H_2.

One H_2 and one O_2 detector in the equipment lockroom. Readouts were via a pen recorder displayed in the vessel's operation control centre. Compartment temperature, relative pressure, N_2 supply line pressure and flow were also displayed.

Back-up detection

Sample tubes at various positions in the compartment were led to the open deck allowing gas samples to be drawn and analysed either in the analysis laboratory or directly with a portable detector.

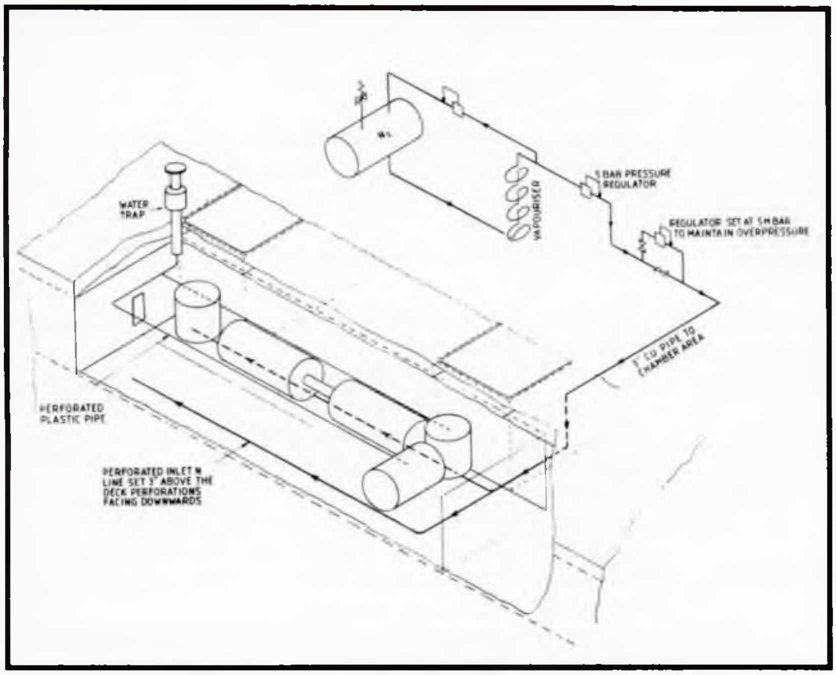

Fig 5: Inerted chamber compartment

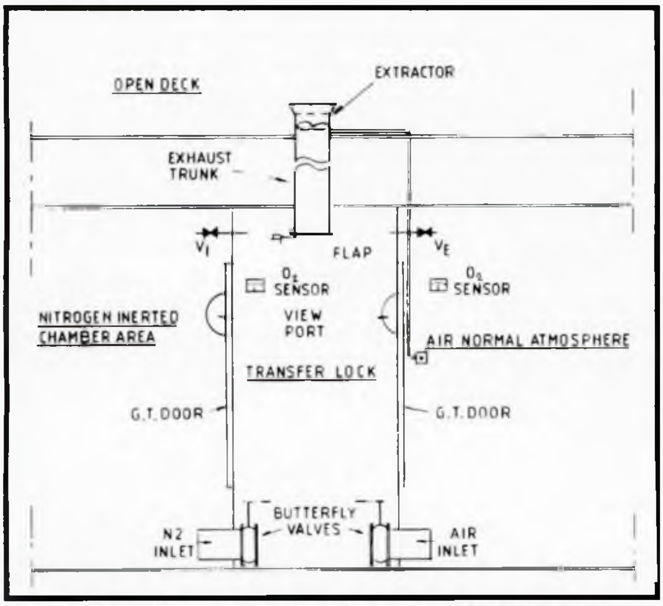

Fig 6: Entrance lock to inerted compartment

THE DIVING SYSTEM

The vessel's outfit consisted of five living chambers, two wet pots, two bells and one transfer lock plus one hyperbaric lifeboat; total volume, 108 m^3. All were rated to 50 bar maximum working pressure.

Only part of the system was used for the Hydreliox dive:

- chambers 4 and 5.
- wet pot 2.
- transfer lock – total volume 50 m^3 (Fig 3).
- bell 2 and contingency for hyperbaric lifeboat.

Six men accomplished the trials living at 500 m of salt water.

The other chambers were kept at an interim pressure and isolated. The trunking between chambers 3 and 4 was inerted to prevent any leakage of H_2 causing contamination elsewhere in the system.

Hydreliox pipework system

The existing gas supply system was replaced by a purpose-built Hydreliox system. Gas panels were installed in the control room on deck and the number of gas lines was reduced to a minimum.

Three pressurisation lines NRV fitted	172 bar
Three decompression lines remotely controlled valves	50 bar
Three pressure gauge lines flow restrictors	50 bar
Three BIBS supplies NRV	65 bar
Four analysis lines flow restrictors	1.5 bar

The existing Heliox pressurisation line remained in service, controlled from the saturation control room. All pipework was manufactured and fitted to high integrity standards.

Life support units (LSUs)

The existing regeneration system was not used and new LSUs were installed on the open deck to allow for access and service. All power supplies were taken from the power supplies container located in a safe area on deck. Two units were fitted, each capable of supporting the whole diving system. Emergency back-up was provided in the chamber by scrubbers and heaters as usual.

Bell dive control

The existing dive control was used but the gas panels were isolated and replaced by panels on deck. This was manned by an additional supervisor supported by direct communication and closed-circuit television monitor.

Bell oxygen

The manual O_2 adding system was disconnected and bell autonomy with respect to O_2 was ensured by keeping the bell at a high O_2 level. O_2 was added after each dive by the automatic O_2 adding system.

Hyperbaric rescue vessel (HRV)

The O_2 adding system was disconnected and the vessel was pressurised with a PO_2 of 700 mbar ensuring 30 h autonomy for six divers. The vessel was normally kept at 200 m, 2% Heliox, and would be pressurised with a Hydreliox-rich mix if required. This would give enough time to recover the HRV to the Comex base in Marseille.

Gas storage

All gas containing H_2 was stored on deck and only Heliox was kept in the existing below-decks gas store. All Hydreliox storage was fitted with remote-controlled pneumatic valves allowing quick isolation in the case of fire or leakage. O_2 was stored on deck as usual.

A water deluge system was fitted over all the gas-containing elements on deck to keep it cool in the event of a fire.

Gas mixtures carried

Hydreliox bottom mix. H_2 47%, O_2 0.9–1.0%, He balance (PO_2 530 mbar).

Heliox bottom mix. For trunk pressurisation and initial pressurisation of chamber system. O_2 0.9–1.0%, He balance.

Hydreliox-rich mix. As bottom mix but with higher O_2 content for therapeutic treatment of deep compression sickness and chamber BIBS. Final HRV pressurisation (if required). H_2 47%, O_2 1.9–2%, He balance.

Hydrogen. As a reserve for mixing bottom mix. Chamber pressurisation from 250 m to storage depth. Control of chamber H_2 content as depleted by lock operations.

Chamber emergency pressurisation mix. Pressurisation of the system in the case of accidental pressure drop.
Chamber flushing in the case of fire/pollution.

High pressure nitrogen. This was used for the inerting of pressure vessels before opening.

- Chamber locks (two pressurisations at 15 bar for each operation)
- LSU soda lime compartment
- Bell's trunk
- Bell's volume (twice only)

Oxygen adding system

Comex developed a system to add O_2 to the chambers, the problem here being that although the chamber atmosphere contained insufficient O_2 for combustion, theoretically any method of adding O_2 must cause some local enrichment thereby putting it into the flammable range.

O_2 consumption by a human body is obviously a function of the activity level and can be taken as 30 l/h (standard temperature and pressure) so that the O_2 quality to be added is small.

The automatic O_2 adding system that was fitted is commercially secret. However, its principle is to add little and often.

The mixing process was monitored by a safety control unit which stops the injection if the temperature rises above a set value. The O_2 concentration near the injection point was also monitored.

This adding system was validated by a series of dives in the test facility in Marseille and functioned without incident for these trials.

DIVING PROGRAMME (Fig 7)

The divers' living depth was 500 m with an excursion from the bell to 520 m.

Pressurisation was to 500 m for 92 h.

Standby period at 500 m before first bell dive was 24 h.

One dive was carried out per day for 8 days.

Decompression to surface took 18 days.

Total time, 32 days.

0–250 m, Heliox (1% O_2 at 250 m).

250–500 m, Hydreliox. A PH_2 of 25 bar was achieved by adding H_2 at a low rate of 290 l/min (standard temperature and pressure) to ensure good mixing.

Chamber living depth was 500 m, PO_2 was 400–450 mbar, relative humidity 50–70%, PCO_2 not more than 5 mbar, temperature 31.5–33°C.

Decompression

H_2 was removed from the gas with the CDU, reducing the pressure to 250 m. Decompression then continued in accordance with normal Heliox procedures (Fig 8).

Division of responsibility

Responsibility as defined by the Merchant Shipping Diving Operations Regulations, SI 116, of 1975 was followed but additionally, the Master of the vessel was responsible for the inerting of the chamber compartment and the maintenance of a safe atmosphere within. The Diving Superintendent was made responsible for the entry of persons to the compartment as this activity was closely related to diving.

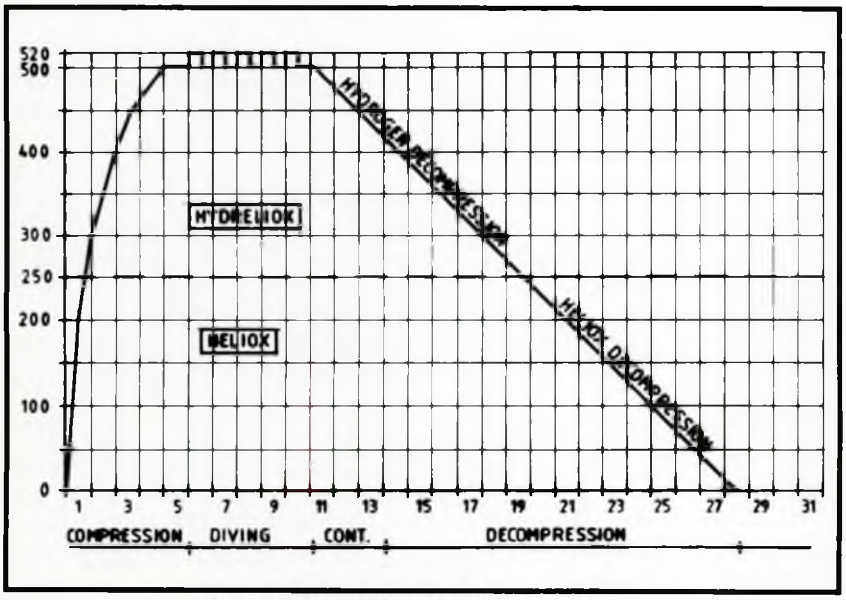

Fig 7: Hydra VIII saturation profile

DIVING TRIAL

Position

In the Mediterranean some $6^1/_2$ miles south of Cassis to the east of Marseille.

Weather

The Mistral was blowing throughout the trial period. Wind speed was 40 knots gusting to 60. Significant wave heights were 1.5 to 2.5 m due to the vessel's position.

Inerting equipment

Initial inerting

Preliminary trials showed that layering techniques were not effective. By using a flush of 800 m^3/h, 2% O_2 was reached in under 3 h. Throughout the dive two men tended the inerting system. Consumption was not high and no emergency flushing had to be carried out so that at the end of the period only 50% of the liquid N_2 had been used.

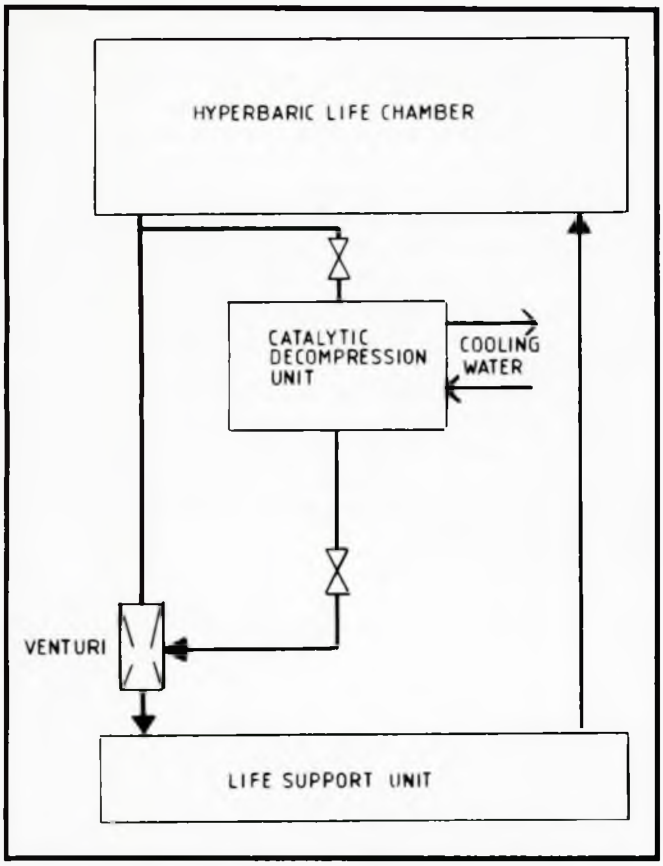

Fig 8: Catalytic decompression unit

Leakage of diving gas

Leaks of diving gas occurred at a low level throughout the trial and the catalyser was used to reduce it. However, at the end of the trial the He content of the chamber compartment atmosphere was 2.24% although this would have been diluted by flushing.

Catalyser in the inerted space

The catalyser worked very well but caused some concern initially when the operating temperatures were above those predicted. However, this gave no problems except to raise the compartment pressure when it was running, typically 10–15% of the time.

Entry to the inerted compartment

A problem occurred with the domestic fresh water supplies to the chambers and the compartment had to be entered. The rebreathers and procedures were found to work well and no problems were experienced. The entry was controlled along the same lines as for a surface dive.

SYNOPSIS OF THE DIVE

Six divers, three each from Comex and the French Navy. Each manned bell run was made with two divers and a bellman.

22/02/88	1000	Divers entered the chambers.
23/02/88	0600	Chambers at 250 m. H_2 introduced into the system.
24/02/88	0600	Chambers at 400 m. Holding for medical checks.
25/02/88	0600	Chambers at 450 m. Held to 1300 for final 50 m. Bell launched unmanned to 510 m. Techniques for securing the umbilical to the bell wire improved.
26/02/88	0600	Chambers at 495 m.
27/02/88	0700	Chambers at 500 m.
28/02/88	1043	First manned bell run. At 1155 bell at 510 m, divers proceeded to a work table where they could carry out a series of specific tasks which were principally related to pipeline work over the next few days. Divers returned to the bell at 1600 and were recovered to the Orelia in 1 h.
29/02/88	1400	Dive to 510 m; dive aborted due to technical difficulties.
01/03/88		Two divers to 530 m, visibility poor and work table vertical movement too great due to gale force winds.
02/03/88		Various safety drills carried out. Bell run with two divers out at 520 m from 1012–1652.
03/03/88		Bell run times reduced due to faster handling of the umbilical; just over 1 h from surface to 500 m. Divers out on the work table for 3 h, confident and working well but recalled due to failure of two body probes.
04/03/88		Satisfactory bell run and work.
05/03/88		Last dive completed satisfactorily. Commenced decompression by burning off the H_2 with the CDU developed for the project. Vessel back alongside in Marseille at 1530.
7/03/88	0700	Chambers at 436 m.
11/03/88	0700	Chambers at 320 m, H_2 disconnected at 308 m.
12/03/88	0100	Chambers at 300 m, N_2 disconnected from chamber space and flushed with air for 2 h before doors opened. Continue decompression as usual for Heliox dive.
24/03/88		Diving team leave the chambers and appear in good health.

ORELIA'S PERFORMANCE

The Orelia's simple lines belie the fact that she is a highly technical vessel built at low capital cost.

Her position keeping in this water depth (520 m) was proven before the diving trials. The weather throughout the trial period was continuously bad; wind speed was 40–60 knots throughout with significant wave heights of between 1.5 and 2.5 m. Despite this, her position keeping was always very good and never caused the slightest problem. The roll and pitch levels of Orelia are similar to a semi-submersible but she was built at much less cost and has fewer deckload limitations than these more complex vessels have. She is fitted with a passive heave compensation system on the diving bells to compensate for the vessel's heave.

When built, the system was rated to 450 m, but the scantlings of the chambers enabled this to be up-rated to 500 m without physical modification and it only required a further hydraulic test on the chambers, trunks and bells.

Her dynamic positioning system is a duplex system with two taut wires, Simrad acoustic and Artemis reference systems controlling six controllable pitch azimuthing thrusters directly driven by diesel engines.

CONCLUSIONS

The diving trials verified that manned diving operations can be effective at these depths and no adverse effects were experienced by the divers, nor were they as exhausted at the end of the trials as they would have been if they had been using a denser gas than H_2.

We are not suggesting that major construction projects could be economically carried out by divers at these depths. However, experience shows that if automatic or remotely operated devices are used there will probably come a time when a fault develops which cannot be rectified by a machine and either human intervention has to be made or the equipment has to be abandoned. Even the US space shuttle has required human intervention for activities that should have been remotely activated and that may be its *raison d'etre* rather than the simple economics of a reusable space craft, which are questionable.

The trials demonstrated that a dynamically positioned ship exists which can effectively deploy divers to 520 m and that this facility can be mobilised relatively quickly to meet the need as it arises. That is far more important to this industry than the fact that the project completed the deepest working diving programme ever carried out.