HYDRA 8 : PRE-COMMERCIAL HYDROGEN DIVING PROJECT

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INTRODUCTION

Deep divers are exposed to 3 types of environmental stresses :

- the High Pressure Nervous Syndrome (HPNS), which is related to the effects of the hydrostatic pressure on the central nervous system. These appear at around 200 metres and increase with depth, causing motor disturbances that may impair divers efficiency.
- the density of the breathing mixture, which increases with depth. Breathing dense gas requires increased ventilatory efforts that may reduce divers work capacity.
- the fatigue of long saturation periods (confinement, thermal stress, bad sleep, lack of appetite, etc..) that is generally related to body weight losses.

To overcome these environmental stresses, scientists have used the properties of the different constituants of the breathing mixtures.

The first deep dive were conducted using Helium as a diluent. Helium has a low molecular weight but no specific anti HPNS properties. The only way of controlling HPNS was to slow down the compression. In 1972, Helium permitted 610 m to be reached during the Comex PHYSALIE VI dive.

In 1975 , the Duke University introduced the concept of the "Pressure Reversal Effect" (Simon et al.,1975). A significant reduction in HPNS was obtained by adding to the Helium/Oxygen mixture a given amount of a narcotic gas, in that case Nitrogen. The new mixture was called "Trimix", but we would rather call it "Nitrogen Trimix" to be more specific.

The possibilities of Nitrogen Trimix were further investigated by different research centers. The two milestones of these experiments were the COMEX JANUS IV open sea dive to 500 m, in 1977, and Duke University ATLANTIS III simulated dive to 685 m, in 1983.

However, the benefit of using Nitrogen to reduce HPNS is counterbalanced by a significant increase in gas density (Nitrogen is seven times heavier than Helium). During the Janus IV dive, the breathing gas, which contained 5% Nitrogen, had a density of 10.5 g/l. It would have been 8.2 g/l with Heliox (22% less). For this reason, a large amount of Nitrogen cannot be used without affecting the diver's ventilatory function.

COMEX HYDRA PROGRAMME

The idea underlying the Hydra Programme was to investigate for a new diving gas that would be both light and narcotic. The only possibility left in the Mendeleiev table was Hydrogen !

Since 1983, four onshore dives using Hydrogen have been conducted at Marseille Hyperbaric Center in collaboration with the US Navy (NMRI), the Swedish Navy (NMD),the French Navy (CERB, CEPISMER, GISMER, CERTSM) and the Centre National de la Recherche Scientifique (CNRS).

The final aim of this programme is to demonstrate the operational feasibility of Hydrogen diving with a deep open sea dive. The code name of this dive will be HYDRA 8.

This paper is intended to present the studies and the developments that have permitted Comex to step from the onshore experimental phase to the offshore operational phase of deep hydrogen diving.

ANIMAL STUDIES

Although Hydrogen is a very active chemical element, previous experiments with monkeys had shown that Hydrogen could be considered as an inert gas from a biological point of view (Brauer et al., 1966, Rostain, 1973).

Comex carried out complementary studies to confirm that Hydrogen is a non toxic molecular gas. In a first series of experiments, 40 mice were exposed for 48 hours at 600m, breathing Hydrogen/Oxygen. Comparison with a reference group exposed to Helium under the same conditions showed neither behavioural change nor any histological sign of toxicity.

Further experiments were then performed to extreme depths to determine any possible limit to Hydrogen use. A group of 120 mice was exposed to depths ranging from 1300 to 2000 m, either with Helium or Hydrogen. The survival rate at 1800 and 2000 m was much higher with Hydrogen than with Helium, which tends to prove that Hydrogen does not develop any toxic effect up to these depths (Gardette, 1986).

Figure no 1 : Fatality rate among mice exposed to extreme depths, breathing either Helium or Hydrogen mixtures.

DEPTH	HELIUM	HYDROGEN
1800 m	60 %	0 %
2000 m	100 %	60 %

MANNED HYDROGEN DIVES

Following the animal studies, Hydrogen diving appeared safe and practical in the depth range that covers human intervention. In June 83, eighteen persons, including Mr HG Delauze, chairman of the company, performed short bounce dives to 75-90 m offshore Marseille, with Hydrogen as bottom mix (Hydra 3). As no incident was recorded (Fructus, 1983), the programme proceeded with deep saturation diving.

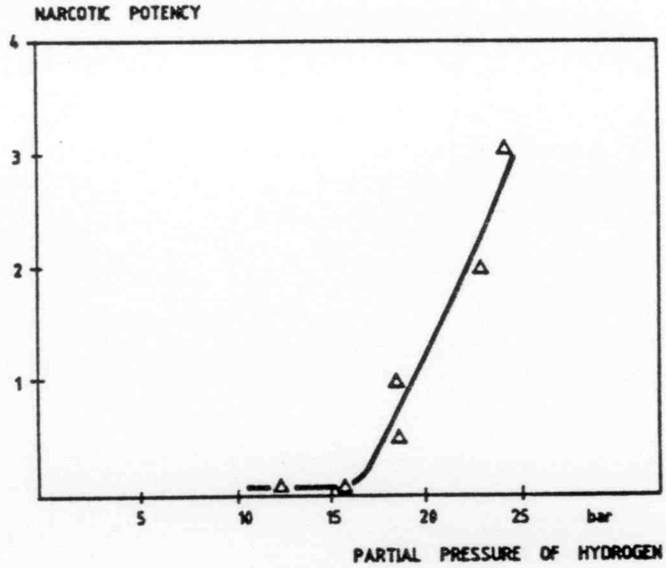
Figure no 2 : Summary of the Comex Hydra programme.

Dive	Depth	Method	Studies
HYDRA 3	75m 90m	Hydrogen bounce dives	- First observations on man
HYDRA 4	120m 300m	Heliox sat with short exposures to Hydrogen (24.5 bar max)	- Quantification of the narcotic potency of Hydrogen in man. - Diver's ergonomy in dry and wet conditions.
HYDRA 5	450m	Hydrogen Trimix saturation (25 bar)	- Pressure reversal effect, - Diver's ergonomy in dry and wet conditions, - Switch from Hydrogen to Helium, - Hydrogen sat. decompression.
HYDRA 6	520m	Hydrogen Trimix saturation (25 bar)	- Validation of procedures for Hydra 8 offshore dive, - Diver's work capacity in water, - Selection of divers,
HYDRA 7	180m 260m	Hydrogen saturation (25 bar max)	- Selection of divers, - Narcotic potency of Hydrogen.

Hydra 4

The primary objective was to quantify the narcotic potency of Hydrogen on man. The dive was a Heliox saturation during which 6 divers were exposed to short periods (1 to 6 hours) of Hydrogen breathing in a specially designed dome. The depth of exposures progressively increased from 120 to 300 m . The narcosis appeared at 180 m in some divers and definitely affected all divers at 240 m, i.e. 24.5 bar of Hydrogen (Carlioz et al., 1984, Fructus et al., 1984, Gardette et al., 1984).

Figure no 3 : Quantification of the narcotic potency of Hydrogen in man according to the scale developed by Fructus (1983), during the Hydra 4 dive.



It thus became apparent that Hydrogen was too narcotic to be used alone as a diluant and that Helium would have to be added to the Hydrogen/Oxygen mixture for further deeper experiments. Hydrogen diving thus became a new version of Trimix, which we would like to call "Hydrogen Trimix".

This experiment also showed a lot of variation in individual susceptibility to Hydrogen narcosis and the need was recognized to select divers with a large saturation experience who tend to be less sensitive.

Hydra 5

The main objective was to reach a significant depth, 450 m, in order to verify the anti-HPNS effect of Hydrogen. The dive was a full scale Hydrogen Trimix saturation and 25 bar of Hydrogen were injected into the chamber during the compression. Effectively, none of the symptoms of HPNS (tremor, dysmetria), or articular pain were observed. Divers did not present the characteristic muscle contractions, restlessness, and felt more relaxed and comfortable. Because of the low gas density, divers could breathe through the nose and did not complain of the "stuffed nose" feeling like in other deep experiments. For the same reason perhaps, they had better appetite and minimized their weight losses after saturation (Gortan and Delauze, 1986).

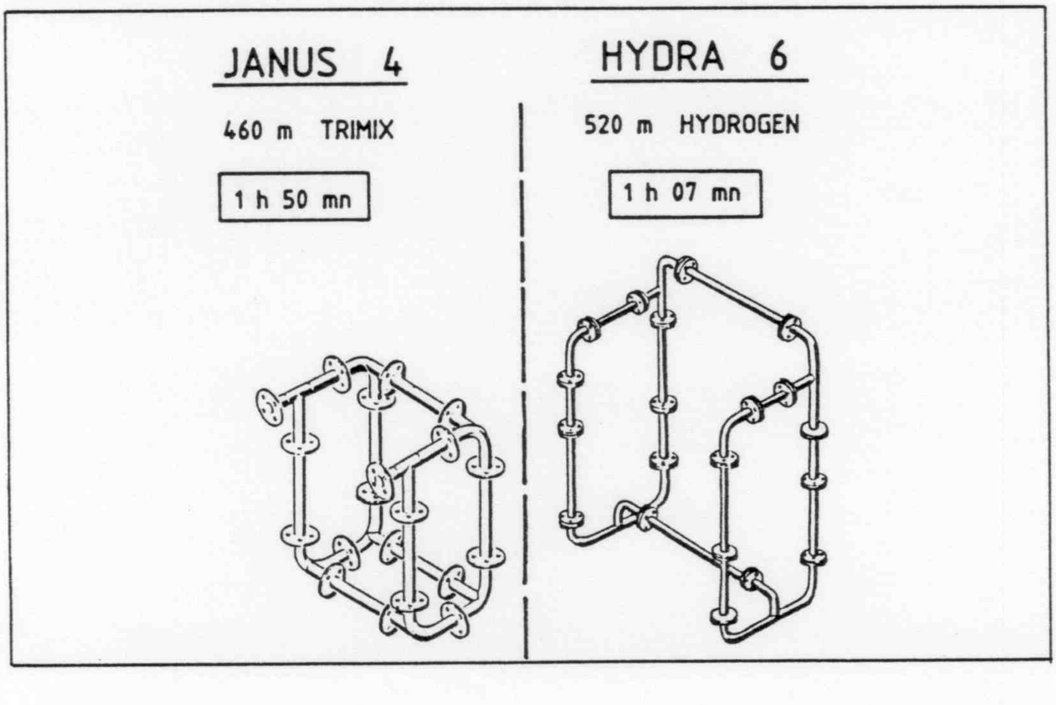
The second objective was to study a procedure that would permit divers to switch from Hydrogen to Helium at the end of the bottom period, thus allowing Heliox decompression. Although the inert gas switch was progressive, using an intermediate gas mixture for 8 hours, divers entering the Helium atmosphere experienced a sudden rise in circulating bubbles. The contingency procedures were immediately applied and the divers were recompressed 20 m with hyperbaric Oxygen on mask, which stopped the bubbles formation.

Similar inert gas switches had been performed during the Hydra 4 dive and had caused no problem of isobaric counter diffusion. It was thus concluded that switching from Hydrogen to Helium could be dangerous and the maximum permitted Hydrogen pressure drop was set to 13 bar in Helium. For deep dives involving more than 13 bar of Hydrogen, final decompressions would have to be performed with a progressive replacement of Hydrogen by Helium inside the chambers.

Hydra 6

This dive was meant to be the onshore validation of the planned open sea dive to 520 m. Its objective was to demonstrate divers work capacity during simulated dives in cold water. Divers wearing full equipment were asked to perform increasing work loads on an ergonometer. The respiratory function tests indicated that divers never experienced ventilatory limitation for graduated work up to 150 W. Divers also carried out specific tasks such as pipe puzzle assembly and their performances appeared to be significantly better with Hydrogen Trimix than with Nitrogen Trimix (Fructus et al., 1987).

Figure no 4 : Comparison of the time required to carry out the pipe puzzle tests during Janus IV experiment on Nitrogen Trimix and during Hydra 6 experiment on Hydrogen Trimix at 450-500 m.



Hydra 7

This next experiment was designed to define a method of selection of divers. During Hydra 6, one of the divers experienced psychological problems of a psychotic type. Medical investigation of his case concluded that the problems could be explained by a lack of saturation diving experience. Four highly experienced saturation divers were thus exposed to the same experimental protocol as during Hydra 4, i.e. increasing depths from 180 to 260 m, but were this time fully saturated with Hydrogen. No sign of narcosis could be measured in the divers which tends to indicate that the narcotic potency of Hydrogen depends on whether the diver is abruptly switched from Helium to Hydrogen or progressively exposed to increasing Hydrogen pressures.

HYDRA 8 OFFSHORE DIVE

This dive is designed to demonstrate the feasibility of Hydrogen diving during a full scale deep offshore dive.

This operation is planned for the 1987/88 winter in the Mediterranean. The underwater site will be located in a depth range of 500 to 520 m. Two teams of divers will carry out various tasks, such as handling, mechanical connection, cutting, etc.. on a base platform lowered from the vessel. Each team will conduct one dive a day, during which 2 divers will perform a minimum of 3 hours of work in the water. The aim is to achieve at least 60 hours work at the bottom in 5 days.

The vessel selected is the DSV ORELIA. The ship, which is under the British flag, is presently being upgraded for Hydrogen diving. The qualification of the ORELIA will be done under the supervision of Bristish DOT, that has already called the DOE for assistance for the diving part of the project. The vessel and the diving equipment will be certified by the Lloyd's R.S.

EQUIPMENT AND PROCEDURES FOR HYDRA 8

Hydrogen diving could only be considered after an extensive study of the risks relevant to the handling of Hydrogen and its use in chamber systems initially designed for Heliox diving.

Fire Risk outside the Chamber System

Fire risk is the obvious concern of Hydrogen diving. The lower explosion limit (LEL) in air is 4% Hydrogen at atmospheric pressure and the maximum permitted Hydrogen level has been set to 2% (50% of the LEL) for Hydrogen diving operations. The margin is thus extremely reduced.

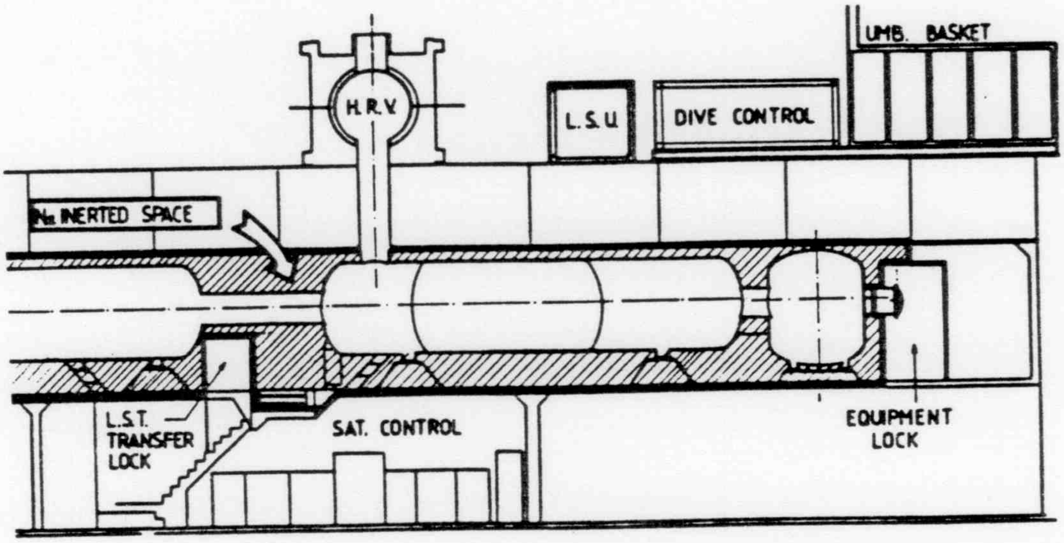
Moreover, Hydrogen is a fast diffusing gas and tends to leak through cylinders, piping and chambers. The saturation system can be designed to minimize the leaks but cannot eliminate them all.

Thus the risk must be prevented of any local formation of Hydrogen pockets in the chamber hall.

Safety of Hydrogen diving first relies on a system of Hydrogen sensors fitted all over the hyperbaric complex to detect minute leaks of Hydrogen. Then, a powerful system of ventilation must be installed to collect and evacuate the Hydrogen leaks. This approach is sufficiant for a well controlled system in an onshore installation and has been retained for the Marseille Hyperbaric Center.

For the planned offshore dive on the Orelia, the problem is more complex. Most of the diving equipment (gas storage, dive control, umbilical storage, life support units, etc...) will be installed on the deck, in the open air. However, for the chamber system, which is located below the deck, no ventilation system could be defined that could cope with a system defect causing a massive leak or an auto-ignition of Hydrogen. It was thus decided to inert the chambers room and liquid Nitrogen will stored on board for this purpose. The inerted sytem is inherently safer than a vented system in that both Oxygen and Hydrogen have to reach critical levels before ignition can take place. Detectors continuously monitor the gas levels and in the event of the flammable limit being approached, steps can be taken in good time to prevent such ignition. The method has also the advantage of being well documented in ship transportation of natural gas.

Figure no 6 : Orelia saturation system as modified for deep Hydrogen diving.



Inerting will require a lot of modifications in the saturation system. Part of the chamber valves will have to be remote controlled and a special cabinet will be installed around the main lock to allow its use from outside the inert area. For spot operations, or in case of an emergency, the LST's will enter the chamber room through a special lock and "dive" the inert area with smoke diving apparatus.

Fire risk inside the chamber system

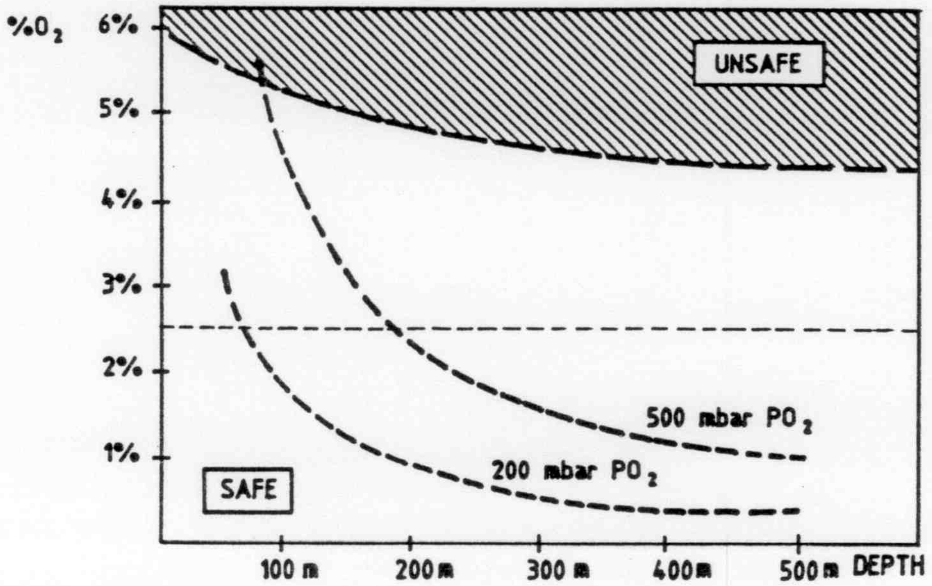
Under pressure, and for different gas concentrations, very few information were available in the literature on the flammability of Hydrogen. Comex had to carry out specific tests to determine what would be the safe limits of use of Hydrogen/Helium/Oxygen mixtures at different depths.

Experiments were conducted in a small explosion chamber where different concentrations of the gases were ignited by high energy welding electrode arcs. The lower explosion limit of Hydrogen in Heliox was found to range from 5.5% at 15 bar to 4.35% at 75 bar, for the concentrations relevant to Hydrogen Trimix diving (Gortan, 1983).

The procedures and equipment were thus designed to insure that at any time, at any location, there is no risk of forming a flammable gas mixture. The maximum permitted Oxygen concentration was set to 2.5% (50% of LEL) inside the saturation system.

Using this value and considering a 500 mbar PO_2 as commonly used in saturation operations, it can be seen from figure below that Hydrogen diving is safe and practical for depths in excess of 200 m (for instance, a typical bottom mix at 300 m contains only 2% Oxygen) and the deeper the saturation depth, the lower the Oxygen concentration and the safer the operations.

Figure no 6 : Flammability threshold of Hydrogen/Helium/Oxygen mixtures versus depth.



Piping, Locks and Trunking

The basic rule in adapting the Orelia saturation system to Hydrogen diving was to limit to a minimum the number and the length of lines carrying Hydrogen mixtures. Each of these circuits will be flushed with either pure Nitrogen or Heliox before and after its use.

To prevent Hydrogen/air contact, locks and bell trunking will be flushed with Nitrogen prior to be opened and all the dumped gas will be collected and evacuated outside through a special venting circuit. The same precaution will be taken on pressurization of the locks or the bell trunking to avoid air to be introduced in the chambers atmosphere. The procedure will consist of a cycle of pressurization/decompression on Heliox before pressure equalization to cut the oxygen concentration down. Similarly, during a dive, the hub of the bell will have to be flushed or flooded before opening of the lower door to prevent contact of a trapped air pocket with bell atmosphere.

A special semi-integrated umbilical will be used to prevent Hydrogen built up in the inter-hoses space. To avoid the use of pneumatic/electrical slippering ring, no umbilical winch will be used and the bell umbilical will be handled with a block and stored in a basket on deck.

Life Support Units

The main difficulty in atmosphere control comes from the need to inject pure Oxygen to compensate for leaks and divers metabolic consumption.

For the chambers, Comex designed and tested a special life support unit adapted to Hydrogen diving. The unit has a high power control of temperature and humidity, as required for deep diving operations, but its key part is the Oxygen addition system. Pure Oxygen is effectively injected in the gas stream but a series of safety devices are installed to :

- ensure good Oxygen mixing,
- prevent any direct connection between Oxygen supply and chamber atmosphere,
- immediately shut off the system in case of an increase in temperature.

The system was used during Hydra 5, 6 and 7 and proved to be very safe and efficient and two of these units will be installed on the Orelia saturation chamber system.

For the bell atmosphere, the Oxygen level will be simply controlled by ventilation with Bottom Mix. The size of the bell is such that with an initial 900 mbar PO_2, there will be sufficient Oxygen inside the bell for three men for 30 hours.

Hydrogen Removal Unit

The design of this unit is related to the problem of decompression. On one hand, abrupt switching from Hydrogen to Helium cannot be considered because of isobaric counter diffusion effects and divers need to start their decompression on Hydrogen. On the other hand, Hydrogen must be removed before the chamber reaches 200 m for safety reasons.

During the Hydra 5 dive, one team of divers was decompressed with progressive ventilation of the chamber with Helium. This procedure proved to be efficient but was rather costly.

Comex thus developed a special unit to selectively remove the chamber Hydrogen during the first phase of the decompression. A stream of chamber gas is directed over a catalysor that combines Hydrogen and Oxygen into water. By controlling the gas flow rate, one can control the amount of Hydrogen removed and thus the chamber ascent rate. The unit was used during Hydra 6 which became the first chemical decompression ever performed. It will be redesigned to adapt to operational use and installed on the Orelia.

Diver's Equipment

Divers equipment was tested during the Hydra 6 dive to 520 m. Divers thermal protection did not differ from conventional deep diving equipment except that a new Comex Pro silicone hot water suit was tested during the dives.

However, for the under water breathing apparatus (UBA), special developments were required. The UBA must function in a gas reclaim mode to prevent Hydrogen bubbles coming up to the surface and accumulating in the moon pool of the vessel. Moreover, the UBA should not work in closed circuit to avoid the problem of pure Oxygen injection.

Two types of equipment were tested, the Comex Pro X-lite helmet associated to the BOS bail-out system and the Lara semi-closed circuit system, which were evaluated during normal and emergency diving situations. Both systems performed well and received good comments from the divers, but the Comex Pro system is likely to be selected because of it compability with the gas reclaim system already installed on the vessel.

Diver's Monitoring and Communications

The divers working in the water will be equipped with a special monitoring system to control the safety of their operation. Individual monitoring will include relative depth to the bell, hot water temperature at suit inlet, inspired gas temperature, rectal temperature and breathing frequency rate.

No special problem of communication has been identified with Hydrogen. Divers voices are distorted but conventional Helium unscramblers seem to work satisfactorily, even though the setting is slightly different than in Helium.

CONCLUSION

The operation comes at a time when deep commercial diving is becoming a reality. Operations are carried out on a routine basis at 300 m in the Campos field in Brazil for instance. New projects in Norway and in Brazil will extend this activity to the 300-450m depth range.

Comex expects that the Hydra 8 dive will demonstrate the advantage of hydrogen diving, i.e. increased work capacity and reduced saturation fatigue and hopes that this technique will open up new markets to the diving industry.

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