2001 September 01

PROCEEDINGS

FIRST INTERNATIONAL ARTHUR - BORNSTEIN - WORKSHOP ON MEDICAL ASPECTS OF DEEP TUNNELING AND DIVING

Editors
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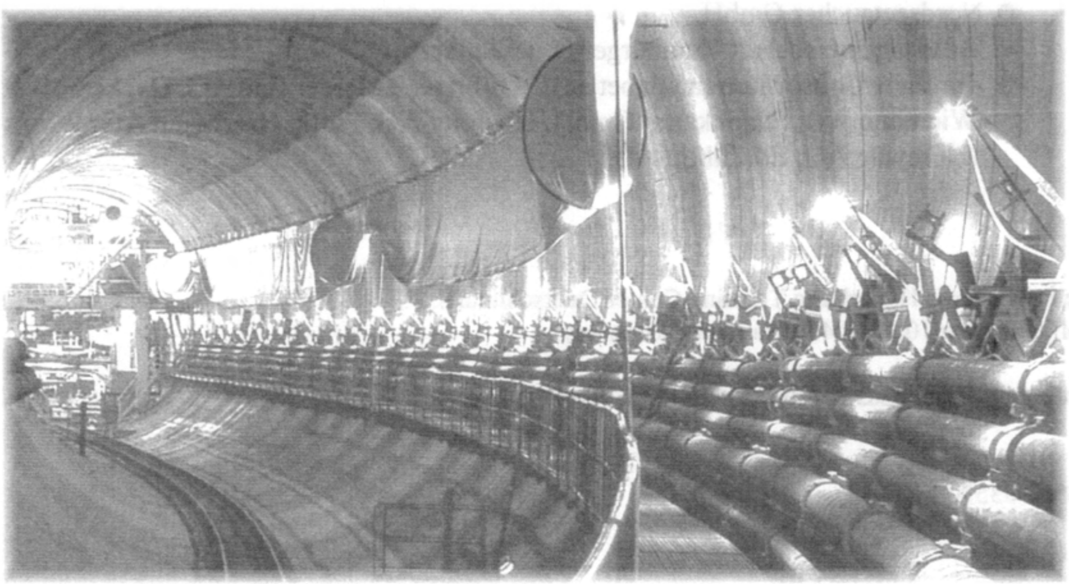


As held in Hamburg, Germany, 1998 May 1 and 2
on the construction site of the "4th Tube Elbetunnel"

The 49th Workshop of the
Undersea and Hyperbaric Medical Society

Hamburg: Hyperbaric Training Center Deutschland e.V.

Faesecke K-P, Sterk W, Hamilton RW, eds. 2001 Sep. Proceedings of the First International Arthur Bornstein Workshop on Medical Aspects of Deep Tunneling and Diving. Hamburg: Hyperbaric Training Center Deutschland e.V.

This document includes the Proceedings of the First International Arthur Bornstein Workshop on Medical Aspects of Deep Tunneling and Diving. The Workshop was held in Hamburg, Germany, 1998 May 1 and 2, on the construction site of the "4th Tube Elbetunnel," the fourth tunnel being added to the original three-tube tunnel under the Elbe River at Hamburg.

The Workshop is recognized as the 49th Workshop of the Undersea and Hyperbaric Medical Society.

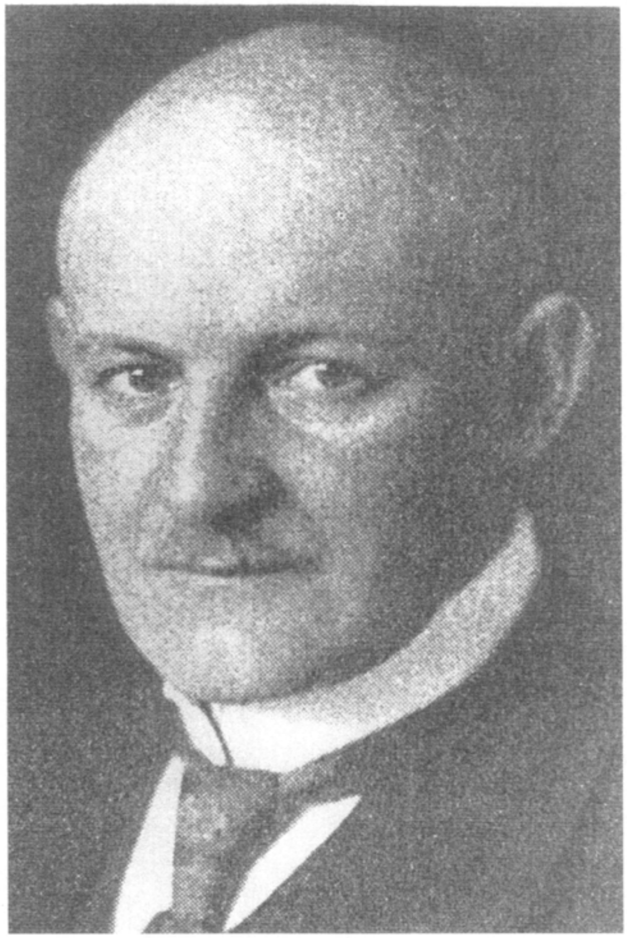
Support for the workshop was graciously provided by

- Hamburg Port Health Center, Maritime Health Department.
- Nordseetaucher GmbH
- Arbeitsgemeinschaft Hamburger Druckluftärzte
- 4th Tube Consortium (alphabetical): Bilfinger + Berger Bau AG; Dyckerhoff & Widmann AG; E.Heitkamp GmbH; Hochtief AG; Philip Holzmann AG; Wayss & Freytag AG; Ed.Züblin AG.

The Publisher is Hyperbaric Training Center Deutschland e.V., Wolfgangsweg 10, D-20459 Hamburg, Germany.

Printing by Druckhaus Fenske, 25421 Pinneberg, Germany

ISBN 3-935908-007-8



This workshop is dedicated to the memory of

Professor Dr. med. Arthur Bornstein

1881, April 14 - 1932, January 2

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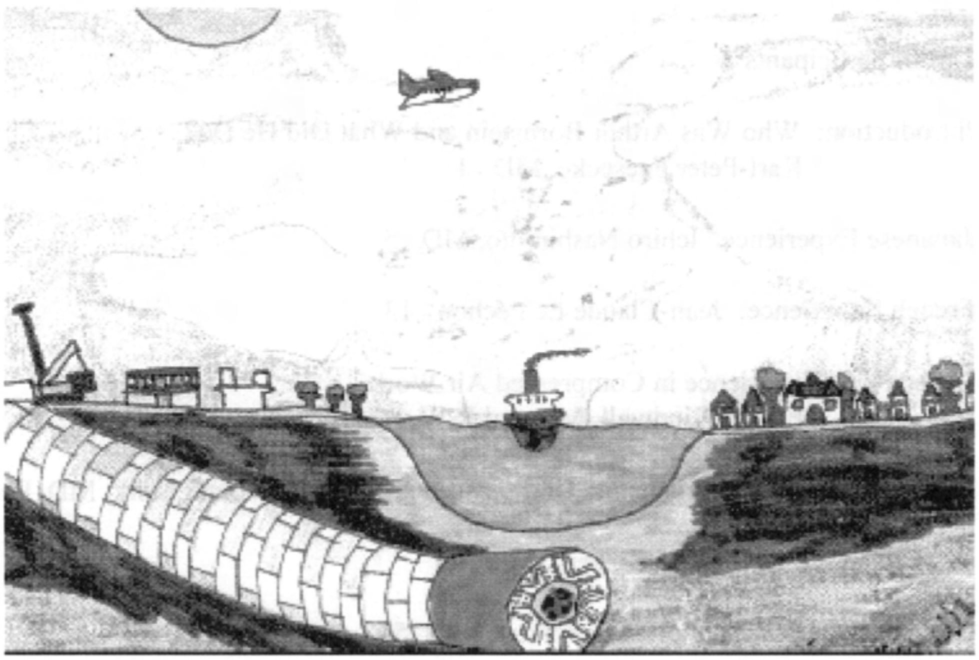

This drawing, original in color, was prepared by 10-year-old Nico Lühmann in December 1997.

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I.

INTRODUCTION: WHO WAS ARTHUR BORNSTEIN AND WHAT DID HE DO?

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This conference, the *First International Arthur-Bornstein-Workshop*, is convened on the International Labor Day, and I appreciate that you have turned up nevertheless. We have come together to discuss actual and forthcoming problems in compressed air work and diving within compressed air work installations. Every one of you has been invited because I expect everyone to give his special input to this meeting. Of course there are also some very special guests, longtime colleagues and personal friends, and I bid them an extra hearty welcome. You may wonder why we have a couple of divers around: it is my principle not only to talk *about* these men, but also *with* them, because they are the ones we work for—none of us doctors would put a tunnel under the Elbe River, but they will.

Now let us consider the question "Who was he, and what did Arthur Bornstein do?" You might have been surprised about the title of this workshop, but those of you who are familiar with the history of diving or have looked into old source books, maybe from the United States Navy back in the forties or fifties, when Charles Shilling started putting literature together, you will find "A. Bornstein" on bone necrosis. First, to show you what this man looked like, his photo is included as the frontispiece of this document. He looked like a real old time German professor. He was born in the early 1880s and already had a distinguished career as assistant professor of neurology behind him at the age of almost thirty when in 1909 he was asked to take over the medical surveillance of the Hamburg Elbe Tunnel which was under construction at that time. They had experienced a lot of health problems; actually there was one worker who had died from decompression sickness. (A couple of weeks ago I discovered the autopsy protocol of this first known German victim of decompression sickness in the leftover material of the abandoned port hospital's pathology department.)

Bornstein came to Hamburg and right away introduced the latest in knowledge on compressed air work. Because at that time the Vienna experience as published widely by Heller, Mager, and von Schroetter in 1,800 pages was available to everyone (Heller et al, 1900). It told everything about decompression sickness, about oxygen, even decompression on oxygen, about tables and treatment, but, for certain reasons, most of them money-related, these tables were not applied in Hamburg. So they ran into a lot of trouble and the workers even went on strike for better decompression schedules—in 1908! Bornstein started a large research project on site, accompanying the construction of the tunnel, and he came out, in the run of three years, with nine - I would call them revolutionary - publications (Bornstein, 1910b).

To start with the most exotic one, he had brought his wife with him, who was also a medical doctor, something still unusual at that time, and she undertook a project of her own. They wanted to know exactly how much blood is inside a living animal, because they had the idea to calculate the amount of nitrogen that goes into a body (Bornstein, 1910a). They had to keep the heart beating, while the animal was bleeding. How could one do this? Fill it up with Ringer's solution! But how could the animal survive? Put it under oxygen in high pressure! So in 1910, on the 5th of May, she had three dogs in a chamber, emptied of blood, filled up with Ringer's solution and kept alive for days under three atmospheres absolute of pure oxygen (Bornstein OA, 1911). That was exactly fifty years before Boerema and his experiments in Den Helder in the Dutch navy chamber. I recently got a letter from Dirk Bakker and he said, well, if Bornstein has the honor, it should go to him. Alas, Boerema is no longer alive, so he will never know. So that was what Dr. Adele Bornstein did; it was a great loss when she died shortly after in her second childbirth.

Arthur Bornstein introduced treatments on oxygen; he tried out on himself how sensitive he was towards oxygen. He worked on a bicycle ergometer in three atmospheres absolute on pure oxygen until a seizure stopped him after 48 minutes. He did it on himself, the first known experiment on oxygen toxicity on a human volunteer (Bornstein and Stroink, 1912). He was a courageous man!

Together with a radiologist from a nearby hospital he discovered aseptic bone necrosis in three compressed air workers (Bornstein and Plate, 1911-1912). He was the first to publish this, not Bassoe! Bassoe was six weeks later, I can prove this. So it might actually be called "Morbus Bornstein."

He introduced oxygen decompression on workers who turned out to be susceptible to the bends or "pressions", as it was called in German, and it was widely applied. He had what they called a "medical lock" (a recompression chamber) on the work site and he made it mandatory that every case of decompression sickness had to be recompressed in that chamber. Because
his predecessor on this job had been convinced that decompression was bad for the workers; it is cold and wet, and the exposure has to be kept as short as possible in order to minimize the bad effects of decompression. Bornstein kind of revolted at all of these ideas (Bornstein, 1912; 1914).

One final publication that came out in 1918 was about "diver's squeeze" (Bornstein, 1918). What happens when a diver falls down from his working depth a couple of meters? Well, we now know but he was the first who did experiments on that. He constructed a diving helmet for rabbits, a very fancy thing, so he could experiment with negative pressure inside the helmet. He even did it on himself. He let himself drop for two meters difference and experienced how much pressure gradient the human thorax can tolerate—and it is not much, as we know.

So I think it is about time to give Arthur Bornstein credit for being the father of German diving medicine. The British have Sir John Haldane, the French of course have Paul Bert, the

Austrians have Heller, Mager and von Schroetter, and we have Bornstein and should be proud of him.

When the tunnels were finished, there are actually two of them next to each other, he became the first professor of pharmacology at the University of Hamburg, which was founded later. He died at the age of fifty, much too early. His son, who was a medical student at that time, later emigrated to the United States, fought in the Pacific theater in WWII, and later settled in Texas as a forensic pathologist; his son and daughter are still alive.

I have done quite a bit of research on Bornstein and felt the obligation to "reanimate" this exceptional personality that has given so much to the diving and compressed air work community, and therefore we named this workshop after him.

References

Bornstein A. 1910a. Eine Methode zur vergleichenden Messung des Herzschlagvolumens beim Menschen. Pflügers Arch 132: 307-318. ("A method for a comparative measurement of man's heart stroke volume.")
This study measured the blood-flow through the lungs by analysing the amount of exhaled nitrogen while pure oxygen was inhaled. Under different work-loads including hot and cold baths the changes in cardiac output were registered and compared very well with bloody methods. Bornstein's idea behind these experiments was to calculate nitrogen uptake during hyperbaric exposure in relation to the actual workload; this in contrast to the fictitious Haldanian tissue saturation.

Bornstein A. 1910b. Versuche über die Prophylaxe der Pressluftkrankheit. Sonderdr. Berl Kl Wschr 47 (27):1-10. ("Experiments on the prophylaxis of compressed air disease.")
This paper was based on a lecture presented to the Hamburg Society of Physicians a few months earlier, where he described the results of his protective actions. One of the first directions he gave after taking up his post had demanded:

- Consequent treatment of all bends' cases in the recompression chamber
- Prophylactic therapy in cases of insufficient decompression
- Introduction of step-wise decompression according to Haldane
- Acceleration of nitrogen wash-out through oxygen-breathing

He claimed the success of all these provisions, thereby decreasing the bends' rate considerably. Among others there is a report on an oxygen test, performed on himself, where he cycled inside his treatment chamber at an absolute pressure of 3 bar for 48 minutes, breathing pure oxygen, before he fell off in an oxygen convulsion.

Bornstein A. 1912. Erfahrungen über Pressluftkrankheit. Vjschr ger Med 44:357-375. ("Experiences in compressed air disease.")
This publication gave a comprehensive overview of his activities during the tunnel construction with special regard to occupational safety and hygiene. Aspects of workers' physical examination were discussed, as well as methods of reducing the incidence of "bends," of which more than 800 were observed and treated during the two years. Detailed statistical analysis of localization of complaints, time intervals, and treatment regimes were given.
It remains a fact that all of Bornstein's suggestions that were implemented in the "Hamburg Senate Regulation for compressed air workers" (1909) and proved successful, a few years later found their way into the first German nation-wide regulations on compressed air work, issued by the government in 1921 and, after many changes, are still effective today.

Bornstein A. 1914. Physiologie und Pathologie des Lebens in verdichteter Luft. Sonderdr. Berl Kl Wschr 51(20):1-18. ("Physiology and pathology of life in compressed air.")
This is the print version of a lecture Bornstein gave in Berlin in November 1913 which covered the complete field of knowledge of the time with regard to hyperbaric exposure. Only five years after starting as the "tunnel-doctor" of the Hamburg Elbe tunnel, Bornstein had become the leading authority in Europe, who combined the findings of his predecessors in the field and developed them further. He presented the first calculations of nitrogen uptake in different circulatory situations, he advocated a concept of decompression that was already based on Behnke's later so-called "oxygen-window" principle and strongly advocated the use of oxygen in therapeutic recompression. He was the first truly modern pioneer of hyperbaric medicine, comprehending all aspects of the field on the basis of own experience and a sound understanding of compressed air pathophysiology.
This paper can still today be used as a primer for the novice doctor making his first steps into the field. It is the only one of Bornstein's publications that found entrance into the UMS-Collection "Key Documents..."; unfortunately it was reproduced in the original format and language, which rendered it quite useless.

Bornstein A. 1918. Die Absturzerkrankung der Taucher. Berl Kl Wschr 55:1198-1200. ("The diver's squeeze.")
Bornstein described a new phenomenon that had occurred a few times in diving practice, but had yet to be explained. He exposed himself inside a hard-hat dress to negative-pressure breathing up to 50 mm Hg and had a diving-dress for rabbits constructed with support by the Dräger Company for animal experiments. The suction effect of the pressure gradient inside the lungs was clearly identified as the causal agent for the consecutive fatal lung edema. This research made the diving community aware of a hitherto neglected risk and led to technical improvements in the air supply of helmet-divers. So Bornstein can justly be named the father of modern German diving medicine, too.

Bornstein A, Plate E. 1911-1912. Über chronische Gelenkveränderungen, entstanden durch Presslufterkrankung. Fortschr Röntg 18 (3):197-206. ("On chronic joint alterations, induced by compressed air disease.")
They presented three cases of hip arthropathies in workers of the recently completed Elbe tunnel-project, who had clearly described necrotic alterations of the joint surface and underlying tissue. As they had also suffered from decompression illness, in part more than once, the cause was described as insufficient decompression after work as well as after therapeutic recompression. This bone infarction theory is still held up today. It is quite evident from the data of publications, that they came out a few weeks ahead of Bassoe from Chicago, who is generally looked at as the "father" of aseptic bone necrosis. This is not the truth: This clinical entity was first observed and described in Hamburg.

Bornstein A, Stroink A. 1912. Über Sauerstoffvergiftung. Deutsch med Wschr 38 (32): 1495-1497. ("On oxygen toxicity.")
This most remarkable publication contains a summary of all oxygen-related experiments carried out during the construction phase of the Elbe tunnel. The pressures ranged from 0.6 bar to 8 bar, the time-span from several months to minutes, the species from rat, cat, dog, monkey to man. The findings of lung pathology were discussed, in contrast to Lorrain Smith, who is still today connected with the pulmonary effect of long-term hyperbaric oxygen (but had only experimented with normobaric oxygen and described the changes as "pneumonia"), Bornstein clearly outlined the character of changes to bronchi and alveoli as comparable to those of irritating gases and consequently used the term "toxicity" for the first time, as we still do today. He also made quite clear that seizures were not induced by lung-related dyspnea and that death was due to seizures and not lung alterations.

Bornstein, Olga Adele. 1911. Über den Einfluss kompromierter Luft auf die Blutbildung. Pflugers Arch 138:609-616.
The observation that a prolonged stay in compressed air led to a decrease in red blood cells brought the researcher to a novel experimental setting: In order to find out whether only the peripheral blood was "anemic" or also the central blood pools, she had to completely exsanguinate the animals and let the heart do the work: By filling up the dogs with liters of Ringer's solution and keeping them in an environment of pure oxygen at 3 bar in the "sanitary lock," as the recompression chamber then was called, she kept them alive for hours without any red blood cells left inside. This was fifty years before Boerema and was the true first observation of "life without blood."

Heller R, Mager W, von Schrotter H. 1900. Luftdruckerkrankungen mit besonderer Berücksichtigung der sogenannten Caissonkrankheit. Vienna: Alfred Holder.

Faesecke, K.-P. 1997 Ein Preßluftarzt für Hamburg. Die medizinischen Forschungsarbeiten von Arthur und Adele Bornstein beim Bau des ersten Hamburger Elbtunnels 1909 - 1910. M.D. Thesis, Hamburg University

II.
JAPANESE EXPERIENCE

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Introduction

It is an honor to be invited to speak at the first international workshop on medical aspects of deep tunneling and diving, designated by the name of Dr. Arthur Bornstein, a pioneer in investigating compressed air illness in Germany. Quite frankly I know I could not have come this far without the close support and encouragement of friends like you, Dr. Faesecke.

As you may know, in Japan, we have long history and a lot of rich experience in compressed air work, which has been usually done for caisson work, as well as in fishery diving and harbor diving.

Caisson Works in Japan

Fiscal Year	Bridge Pier Foundation	Shaft of Tunnel	Others	Total
1995	55	10	8	73
1996	31	4	7	42

Table I. Maximum working pressure: 0.8 to 4.3 kg/cm^2.

Table I summarizes the number of caisson works in the fiscal years of 1995 and 1996. As you see in the table, the total number of caisson works was 73 in 1995. Out of 73, 55 were for the construction of a bridge pier foundation, 10 were for the vertical shaft of tunnel, and 8 were for others. In 1996 the total number was 42, of which 31 were for bridge pier foundation, 4 were for shaft, and 7 were for others. Most of them were done to build bridge pier foundations. Maximum working pressures ranged from 0.8 to 4.3 kg/cm^2. Since I started the study of the prevention and treatment of decompression sickness (DCS) at a laboratory of Tokyo Medical and Dental University in 1952, I have paid visits many times to the work site of caisson workers and working divers.

Figure 1 shows a caisson work for the construction of a sewage treatment plant at a soft ground area. Figure 2

Figure 1. Caisson for the construction of a sewage treatment plant.

shows a helmet diver preparing for his dive. He was engaged in harbor construction work. The purpose of my visits to the job sites is first to gather various data such as decompression profiles, occurrence of DCS, and bubble appearance in divers by using Doppler ultrasonic techniques as shown in Figure 3. It shows me doing bubble monitoring on a helmet diver shortly after surfacing. The second purpose of my visits to the work sites is to listen to their habits, experience and empirical ways in preventing and treating DCS. I liked to chat informally with caisson workers or divers about their work and life, sometimes over beer or sake (Japanese wine) in the evening. I have given this activity the name of "night diving on the ground." Most of them accepted me as a congenial friend and I have obtained much interesting and valuable information from them through such heart to heart talks and have learned the reality of caisson work and diving work.


Figure 2. Harbor helmet diver.

In time this habit of getting together informally with caisson workers and divers was called "joining Nashimoto's Night Diving Club." I have also enjoyed such "Night Diving" with such colleagues and friends as Drs. Bill Hamilton, Walter Sterk, Eric Kindwall, Hans Ornhagen, and many others when I saw them at EUBS or UHMS meetings. In my judgement, they have been excellent "Night Divers." I will be very happy if my talk about the situation of caisson and diving work and my experience in Japan could contribute a little to the safety and health or welfare of compressed air workers and working divers around the world.

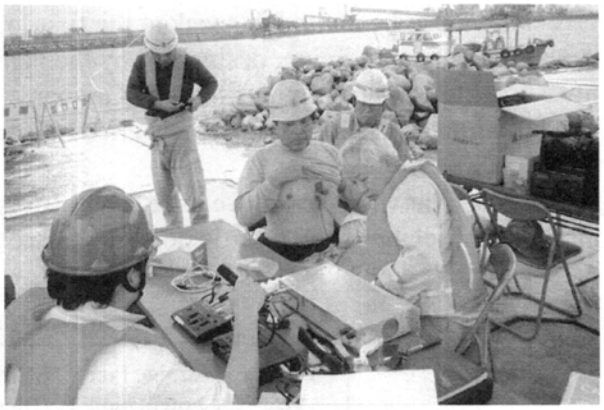
Figure 3. Doppler monitoring in a helmet diver.

Top construction project requiring compressed air work in Japan

In my presentation I followed the outline given by Dr. Faesecke which I trust will easily make clear the different situations among different countries. First of all I would like to report about the Meiko West Bridge project. In this case, pneumatic deep caisson work was employed for the construction of a bridge pier foundation south of Nagoya (located between Tokyo and Osaka and almost in the middle of the mainland of Japan). The maximum depth of the caisson was 45 meters. The caisson work was done using an unmanned excavation system when the working pressure exceeded 2.0 kg/cm^2 (approximately 3 atm abs). Workers sometimes entered the caisson for maintenance or repair of the equipment. They usually breathed air in the caisson but breathed helium, nitrogen, oxygen mixed gas (trimix) in case the working pressure became more than 3 kg/cm^2 G (4 atm). Trimix breathing was mainly used to prevent nitrogen narcosis.

Figure 4 gives a view of the caisson work for the construction of the new bridge's pier P2, looking down from the old Meiko West Bridge. The Meiko West Bridge project had two construction sites, namely the West End Substructure Work to build Piers 1 and 2, and the East End Substructure Work for Piers 3 and 4. For both sites caisson works were executed using unmanned excavation systems and trimix breathing at greater depth. I am not a civil engineer and have little knowledge of civil engineering so I am afraid that I cannot explain this project fully to you. To make up for my rough explanation I may refer to the photocopies of a pamphlet on the Meiko project in English which has been handed out to you. The features of the project were to make a new bridge parallel and near to the existing old bridge. This required very accurate construction in order not to damage the old bridge. The ROVO (Robotized Operating Vertical shield system of Ohmoto pneumatic caisson) unmanned excavation method was used. This means that the excavation and removal of the soil from the caisson were handled by operators at atmospheric conditions outside the caisson as schematized in Figure 5. The system has been described in detail by Hirata et al (1994). As said before, every now and then engineers had to go under pressure for maintenance and repairs of the system. At greater pressures they breathed trimix to prevent nitrogen narcosis. The construction work was completed successfully in 1995 and the pressure inside the caisson was over 4.0 kg/cm^2. This was the very first time that trimix gas was used for caisson work not only in Japan but also in the world. We at that time found a number of problems in the method that needed modification but it had certainly proved its usefulness. At this point I want to mention that the special decompression schedules used for the prevention of DCS during the P2 caisson work had been developed by Prof. Walter Sterk. He joined in our project and all procedures were successfully completed without any DCS requiring recompression treatment. I think that such international cooperation will open new opportunities to stimulate the growth of this field on a worldwide basis. It is the same spirit as of your "First International Workshop."

Figure 4. Caisson for the new bridge as seen from the old Meiko West Bridge.

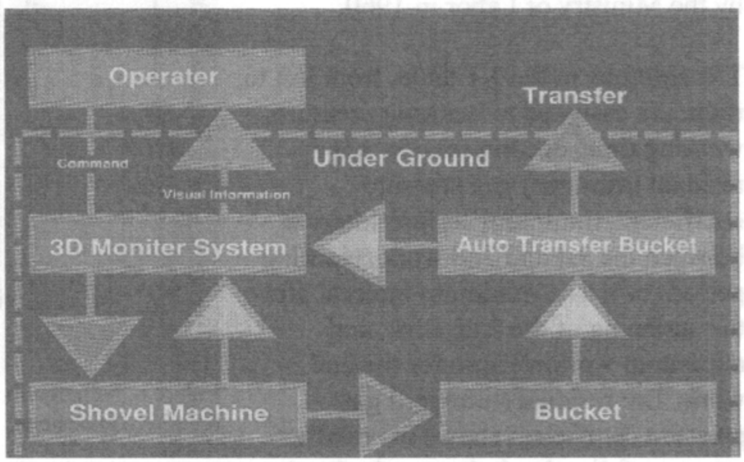

Figure 5. Schematic drawing of the ROVO system

Japanese legislation and safety rules

In 1960 the Japanese Ministry of Labor issued an "Ordinance on the Prevention of Health Hazards under High Pressure" to prevent health hazards in compressed air work and diving work. The ordinance was amended by 1986 and its name changed to "The Ordinance on the Safety and Health of Work under High Pressure in 1977." It's contents are general provisions for facilities for compressed air work and diving work, management of compressed air work and diving operations, medical examination and prohibition of employment of the sick, recompression chamber, and licenses and notification of plans. The ordinance was issued about 40 years ago and has not always been well adapted to the present situation of such works. The Ministry of Labor is however not active to amend it as serious accidents in these works have not occurred or have not been reported.

Decompression schedules

Next I would like to address the topics of maximum work and decompression schedules for compressed air work and air diving operations in Japan. To prevent decompression sickness we have used the J-1 table for compressed air work and the J-2 table for diving and compressed air work at the working pressures more than 4 kg/cm^2 (4 bar). Both tables were issued by the Ministry of Labor in 1960.

The columns in the J-1 table, from left to right, are assigned to working pressure, working time, decompression stops, residual (nitrogen) gas pressure coefficient, minimum surface interval between the 1st and 2nd work (working period) of a day, minimum interval after the surfacing of the 2nd work, and maximum working time for the 2nd work. The residual (nitrogen) gas pressure coefficient shows the relative amount of dissolved nitrogen in the slow compartment having a halftime of 120 minutes. The columns in the J-2 table, from left to right, are assigned to working pressure, or diving depth, working time (or bottom time), decompression stops, residual (nitrogen) gas pressure coefficient, minimum surface interval between works, minimum interval after surfacing of the final work of a day for the next day, and total working time in a day.

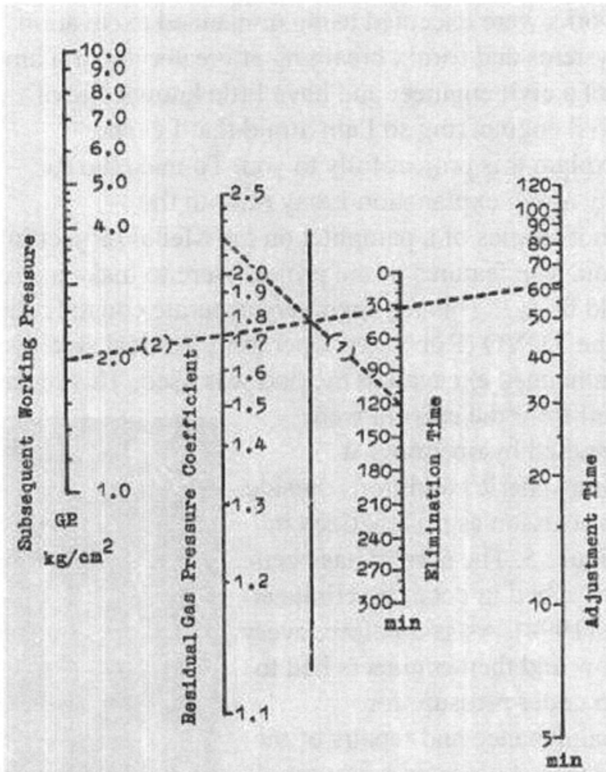

Figure 6. Nomogram to obtain "Adjustment Time" for repetitive exposures.

Figure 6 displays a nomogram to obtain the time to adjust the decompression schedule for the subsequent work. By giving the values of the residual gas pressure coefficient, the surface interval between two successive works referred to as elimination time, and the subsequent working pressure in the nomogram, we can obtain adjustment time and the simple addition of this adjustment time to an actual working time gives a schedule which will be suitable for successive work. Now I would like to show you examples of problems on the J-1 table. Figure 7 is a picture of a caisson work to construct a bridge pier at Ohigawa River. The work was done from the


Figure 7. Caisson work at Ohigawa River, 1977.

Working Pressure (bar)	Working Period (min)	Decompression up to first stop (min)	Stop Times (min) at Different Pressure (bar) 1.5	1.2	0.9	0.6	0.3	Total Decompression Time (min)
2.8	30	7					5	13
	60	6				10	30	48
	90	6				20	60	88
	120	5			10	30	70	118
	150	5			15	35	75	133
	180	4		5	20	40	75	148
	210	4		5	25	40	80	158
3.0	30	7					10	18
	60	6				15	35	58
	90	6			5	20	65	99
	120	6			15	35	70	129
	150	5		5	20	35	75	144
	180	5		5	25	40	80	159
	210	5		10	30	45	80	174
3.2	30	8					10	19
	60	7				20	40	69
	90	6			10	30	65	114
	120	5		5	15	40	70	139
	150	5		10	25	40	75	159
	180	5		10	30	45	80	174
	195	5	5	10	30	45	80	180

Figure 8. Modified J-1 (M) table for the Ohigawa caisson project.

beginning of 1997 to the middle of May 1997. From the result of trial digging, maximum working pressure was estimated at 3.4 kg/cm^2 in gauge (4.4 atm abs). In reply to the request of the site manager, who eagerly wished to prevent DCS at higher pressures, I calculated decompression schedules for the workers exposed from 2.6 to 3.4 kg/cm^2 G.

Figure 8 shows this table, which I drew up on reference to the Blackpool table and the J-1 table. It is far more conservative than the J-1. To prevent DCS more effectively, we recommended oxygen breathing to the caisson workers after surfacing.

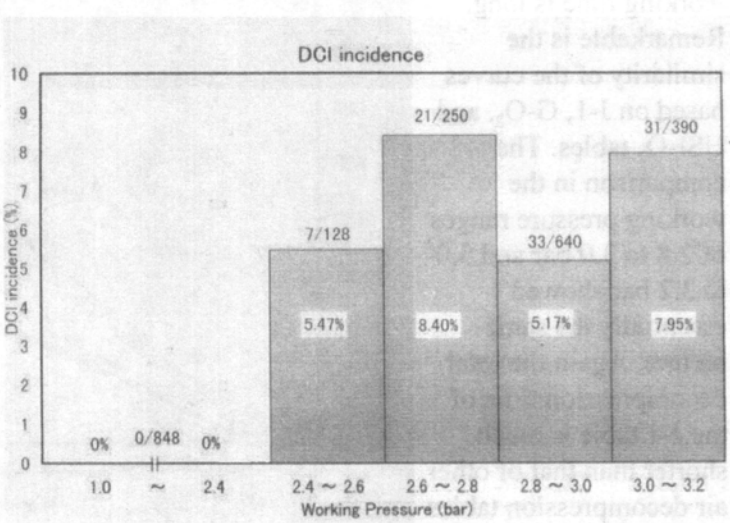

Figure 9. DCI incidence on modified J-1 (M) table during the Ohigawa caisson project.

The bar graph in Figure 9 shows the DCS rate at different pressures in the caisson work. As you see in the graph DCS occurred at high rates at more than 2.6 kg/cm^2 G. The results were contrary to our expectations. Oxygen breathing after surfacing was not effective against DCS. From these results we assumed that the DCS rates would have been much higher if J-1 schedules had been used.

I have compared various tables for compressed air work as far as the working time (WT) versus total decompression time (TDT) are concerned. The tables used for comparison with the Japanese J-1 table are:

British Blackpool table (BP).
Modified J-1 table (J-1M)
German air table (G-Air).
German oxygen decompression table (G-O_2).
US interim table (USI-Air)
US interim oxygen decompression table (USI-O_2)
DCIEM table

Some of the results are depicted in Figure 10. In this graph working pressure ranges from 2.6 to 2.8 bar gauge where bar is substantially the same as kg/cm^2. Working time in minutes is displayed on the x-axis while the ordinate (y-axis) shows total decompression time in minutes. As can be seen from the graph the total decompression time of the J-1 table is very short when working time is long. Remarkable is the similarity of the curves based on J-1, G-O_2, and USI-O_2 tables. The comparison in the working pressure ranges of 2.8 to 3.0 bar and 3.0 to 3.2 bar showed essentially the same picture. Again the total decompression time of the J-1 table is much shorter than that of other air decompression tables and the J-1 curve is close to G-O_2 and USI-

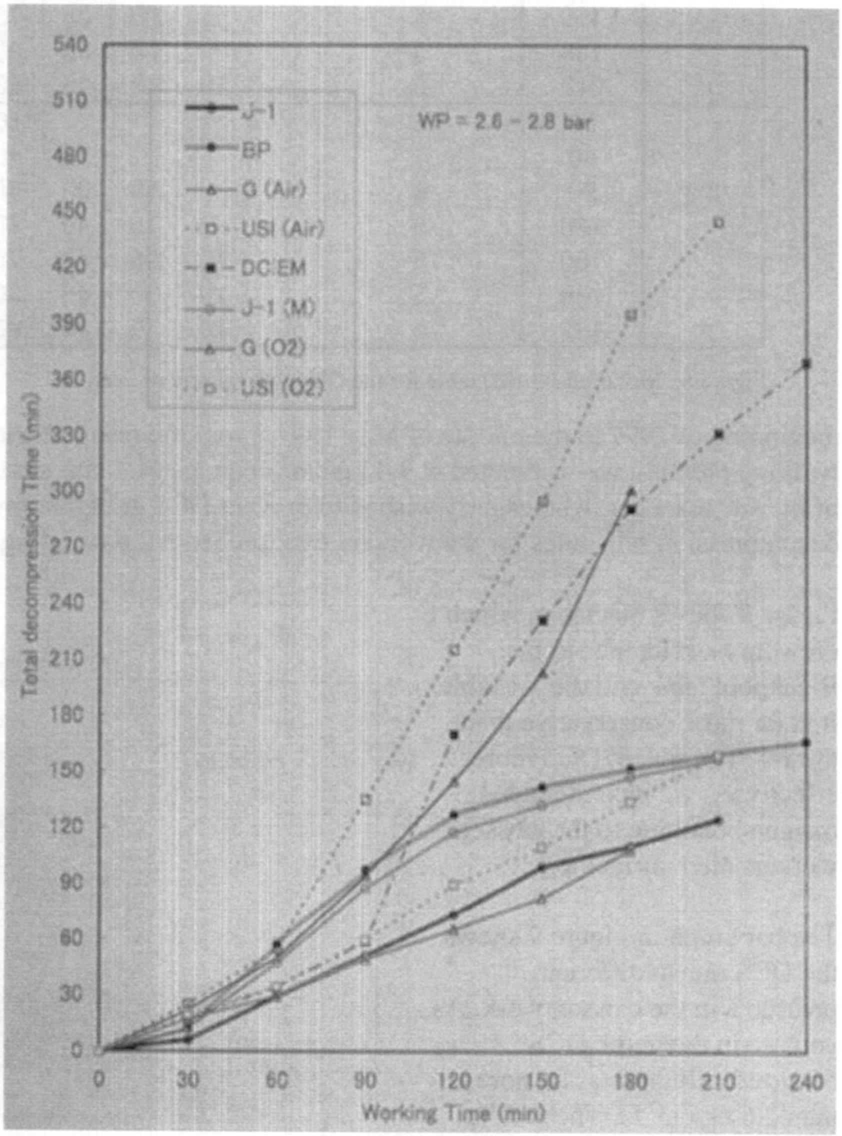

Figure 10. Comparison of various decompression tables for compressed air work.

O_2 tables.

The same counts for the J-2 table when compared to various other diving decompression tables like US Navy, Royal Navy, DCIEM, and the Swiss (Buhlmann's) table. Since the J-1 and J-2 tables issued by the Ministry of Labor in Japan were developed 38 years ago and could be improved, we plan to gather more data and reflect the results of data analysis into improvement of the decompression tables.

Oxygen decompression: Yes or no and how

It is a well-known fact that oxygen decompression is effective in preventing DCS as well as in shortening decompression time. We tried to use oxygen decompression in a caisson work at Wakayama in 1959. At that time there were usually two shifts per day, so-called split shift. The total working time was from 3.5 to 6 hours and working pressure ranged from 30 to 34 psi. An airlock was equipped with sets of O_2 breathing apparatus, which were provided with demand regulators (but without a dump system). To make sure the workers breathed O_2 and to detect the onset of O_2 poisoning, an inspector stayed with them in the air lock during decompression. Oxygen breathing started when the 1st stop of decompression was reached. In the total of 85 trials, 70 men used O_2 breathing and 15 didn't. In the non-oxygen group, 8 cases of bends occurred while there was only one in the O_2 group. Further, all of the members of the non-oxygen group suffered from itches whereas no itches were found in the O_2 group. The total decompression time was about from one half to two thirds of the air only decompression table. Unfortunately, ten days after the beginning of the test a fire accident occurred during decompression when one worker struck a match to smoke which was against the rules and the inspector was not with the workers in the air lock. Six workers died and two others were seriously burnt and we were obliged to stop our test. From this bitter experience we had developed an O_2 breathing apparatus having an overboard dump system.

As another possibility for using oxygen, I considered oxygen breathing after surfacing in a caisson work at Haneda. The working pressure in this caisson would exceed 3 kg/cm^2 and on similar occasions many cases of DCS occurred among the caisson workers. So a site manager sought my opinion on how to fight against DCS. My advice to him was to use a single shift instead of split shift and to use post decompression oxygen breathing (PDOB). Figure 11 shows caisson workers breathing oxygen after surfacing at a resting room. Oxygen rich expired gas was eliminated into the open air through an exhaust pipe. The DCI rate dropped after the change to single shift and PDOB. However when the caisson work reached greater depths and working pressure became higher the DCS rate became higher. On the other hand, during the caisson work at Ohigawa in 1997, PDOB was not effective in preventing DCS. This may be due to the time delay between surfacing and the start of O_2 breathing.

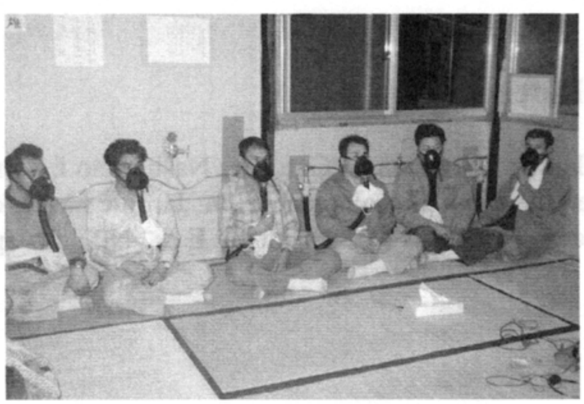

Figure 11. Post decompression oxygen breathing .

Therapeutic regimes

Recompression chambers at the work site of compressed air work and diving were usually not equipped with oxygen breathing apparatus. This is for the prevention of fire accidents as well as acute O_2 poisoning. So in case recompression treatment for DCS was carried out without the attendance of a physician at the work site, recompression was done using Air Table 1a or 2a. At a hospital having a hyperbaric chamber Oxygen Treatment Table 5 or 6 or HBOT schedules are used.

Medical fitness tests

Article 38 of the ordinance on safety and health of work under pressure indicates six items of medical examination for compressed air workers or divers. They include investigation into past history and also on previous experience in work under high pressure as well as a thorough physical examination. For those interested, I can provide them with a photocopy of the ordinance in English.

Compulsory training and qualification for doctors and paramedics

There are no rules on this matter.

Recompression therapy on site with or without a doctor

Article 42 of our ordinance indicates that a recompression chamber at the site of compressed air work or diving work is required in case the working pressure exceeds 1.0 kg/cm^2 or the diving depth exceeds 10 meters. Only a person who has received special education is allowed to operate the recompression chamber.

Any other national specialities

Our ordinance includes both compressed air work and diving work. This may complicate the matter.

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III.
FRENCH EXPERIENCE

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Introduction

This presentation discusses what we are doing in France. Before going to the actual subject I want to make two short remarks.

The first is to underline that what I am saying is my own opinion, I am not speaking on behalf of any organization, ministry of labor, or whatever, and certainly not the opinion of my clients. Probably they have similar ideas, but they have diverse experiences and they may not have all the same conclusions.

Secondly, for most of these people running compressed air in France, safety in compressed air is absolutely not focused on avoiding decompression sickness. This is a very minor consideration among their problems. They are more concerned with welding or burning under pressure, falling down into the working area, or the quality of the atmosphere after welding or cutting or burning. Decompression sickness is not a very big concern for them.

And you will maybe understand better after you see how the system is organized and the limitations that are given to the exposures. In addition the quality of a decompression of course is attached to the tables being used. But I can tell you that the same tables in different operations with different management give significantly different results. A set of tables is good in a context of organization. The organization is a very significant factor in the safety of the tables. We had opportunities to see the same machine with the same people running the machine but with a different management because of a change due to the duration of the project. And the statistical results on the decompression sickness rate has been significantly different just by organization. They were playing the same game but with a different type of organization and concern and practical applications. So it is not enough to consider tables. It is very important to consider how they are implemented in an operation. These were the preliminary things I wanted to tell you.

I did not bring along slides of machines; you have seen the biggest one here and I think any other one will be a small thing, even if there are from different makers, different sizes, and use different boring techniques and pressure balancing methods.

For pressure units I use gauge pressure for all operational data, in bar, and in metres (metres of sea water) for depths, and all partial pressures are in bar.

Construction projects

Past

French companies in the last 10 years have been involved in 42 tunneling projects involving compressed air works in France (and worldwide where there were French companies involved). Types of operations include 0.2 bar manual digging in small diameter tunneling operations to very big machines like in Sydney where it is 12 metres diameter; in Paris we had a metro project in the range of 10 metres also. So there has been many cases with different machines, different makes, and even manual digging, so we had the full range of compressed air work—mostly in tunneling up to 3.3 bar.

Future

The 4 projects that are listed here are those which are just starting, or in consideration now, or in progress.

The SOCATOP project was and I say "was" because it has been postponed, a very large project, with a machine of the same make as the Hamburg one, a little smaller, 12 metres which was prepared to run a 7 kilometres drive close to Paris. This has been postponed for legal reasons in the contracts; it will probably take place within two years. The machine is built. The maximum expected pressure was 6 bar and should hyperbaric interventions be needed, breathing something else than air is considered.

Starting next month a sewage water collection tunnel (Colombes), 4 metre diameter, is going to use compressed air work in case the machine needs visits or repairs. It is the same type of principle as here in Hamburg, it is a Herrenknecht TMB. Each year in the Paris area this type of project covers about 5 kilometres of tunneling operations, some of them being open mode (no compressed air works), depending on the ground conditions. Some of them use compressed air from time to time (1.2 to 3 bar).

There is a new project for a metro line in Rennes in Brittany for which there is provision for compressed air. The TMB is a FCB machine and each drive between the stations is 400 metres. The experience with this machine took place in Lille for a metro line; it is used again in a different town (to answer this morning's question). This is the second operation with the same machine, which on the first project never required compressed air work. This is mostly due to the 400 metres drives that when perfectly adapted to the ground the machine can perform without hyperbaric inspection or repair. In the next station there is access to the wheel at atmospheric pressure and inspection or repair are at atmospheric pressure. In Rennes they are guessing the same. So the airlock system is built-in, it will be tested, there will be a group of people ready to undertake compressed air works, and should they need a task force they will use divers.

In addition there are several international projects in which a French company is at least in a partnership. In Cairo, the metro has used 2 Herrenknecht machines for 3 years. And the same group have just signed a new contract for reusing one of these machines.

In Dusseldorf there is another project here in Germany using the second machine from Cairo, so you understand the machine can be reused.

There is the Sydney metro tunnel which is under construction in partnership between Bouygues and Transfield, an Australian company.

There is a project in Chili with a machine that is a compressed air scrapper. It is similar to the type of machine that you have seen in Dr. Nashimoto's presentation except that it is horizontal and in a tunnel. It digs under pressure and it is not controlled by a computer but manually by an operator watching the scrapper through a glass window. When you have a block or when you need a repair you can enter the chamber; it is low pressure (1.2 bar) in Chili. There is another machine from the same company working presently in Hong Kong which is entirely manned and operated by local people.

Commercial air diving

As far as diving projects are concerned, we don't have any. Very simply, there is no offshore in France, and there are no large diving projects except regular diving operations in dams, rivers, and marine engineering or maritime works. Presently there are no significant diving projects requiring new technology in France. French oil companies like Total and Elf are involved in foreign places. They run some saturation diving, mostly with local companies; there is no more saturation capability in French companies because we don't need it and there is no market.

Compressed air works = Compressed gas work

With regard to national regulations, we have several aspects to address:

Safety organization

We are working under the European directive on safety coordination which has been imposed in France since 1993; this concerns the relationship between the contractor and his client in organizing safety. This directive it is not intended to rule compressed air work or diving. However it has changed a lot the relationship between the contractor and his client, because now all the safety involvement of both are better specified. And this has been extremely useful in diving and in compressed air work to improve the safety because the client is now legally concerned and has some duties from this directive. The reason for showing that regulation here is, "It does change things."

Safety of hyperbaric works

Secondly, we have a decree for hyperbaric works (1990 March 28). We have a single book that covers any work under pressure, whatever the reason for it. It includes all categories of professional divers, HBO_2 attendants, and compressed air workers; it is the same regulation with special chapters for each occupation. This single text, published in 1990 and updated in 1992 has put together all previously existing rules, changing and upgrading them (Direction des Journaux Officiels, 1992). I am sorry the rule is in French, but there is a partial English translation made by the UK HSE. Maybe some of you who have had the copies of these a long time ago have made a German translation.

Maximum pressure

Commercial air diving maximum depth is 60 msw. We have another restriction, which is a commercial diver should not spend more than 3 hours per day in the water, including decompression if decompression is in the water. So the deeper you go, the less time you can work. But you can reduce in-water decompression times by using any means. It means oxygen decompression, nitrox diving, or Transfer Under Pressure, or surface decompression (oxygen only). However this should remain in accordance with the tables published in that book. For saturated divers this 3 hour limit is extended to a 8 hour bell run.

Published official tables cover air diving and air decompression, oxygen decompression (6 msw maximum in water and 12 msw if you are in a wet bell and attached so that in case you have a seizure you will not drown), multiple levels, nitrox (oxygen-enriched air), altitude, repetitive dives. You may use other tables if you wish, you only have to ask for a special authorization from the ministry of labor and support the request with a demonstration of the validity of the proposed procedure. For example, when a foreign company wants to use their own tables in France they can apply for authorization.

If it is not air diving but mixed gas diving a full set of mixed gas tables are provided, down to 200 msw using heliox mixes. If you prefer to use trimix you have to go through special authorization. And this special authorization has already been obtained for trimix diving so it is an open possibility.

Emergency recompression

First of all we do not call "treatment tables" treatment tables, we called them "emergency recompression tables." They are not intended to be used only by doctors. Recompression "treatment" or procedure should be started even before the doctor is here. This the reason for the wording. The words "medical"and "treatment" have been removed. An emergency recompression chamber is never called a "medical chamber" or "medical lock." A medical chamber is in the hospital, not on site. On site is a first aid emergency recompression chamber. We have 2 tables published. One is a recompression to 1.2 bar abs on pure oxygen breathing, and this is for "bends only" type of decompression cases. The other one is the so-called "COMEX 30 table" which is a heliox 50/50 and oxygen breathing table with recompression to 3 bar abs. This is in the book that you have seen for commercial diving.

Compressed air works

General rules

Compressed air work now

In France we no longer use the words "compressed air works" we use the word "hyperbaric works" (compressed gas work). Because air is "air," it is 21% oxygen in nitrogen. And compressed gas work is working under pressure with whatever breathing mixture. And from that you can understand immediately that there is no restriction about maximum pressure; presently it is 70 bar, since one person has been compressed to 70 bar in France.

Gas partial pressures

There are restrictions on the partial pressures of the gases that you are allowed to breathe. The restriction on nitrogen is 5.6 bar, which is air at 6 bar or 60 msw. So if you want to breath something at 8 bar or 80 msw you must have something else than air. So the maximum pressure of breathing air is 6 bar even for compressed gas work, but of course you can use trimix at lower pressures even if it is not required by law. And personally I would recommend any compressed gas work more than 4 bar to use trimix or heliox depending on who wants to do it. But trimix has many physiological, operational, and economic advantages. So the tables for compressed air exposures in the dry are published in the book up to 6 bar on air, and you have 2 specific tables: Decompression on Air or Decompression on Oxygen. Very different from air diving tables, they are adapted to compressed air work. They are longer in duration of decompression for similar exposures in diving and, at least in a range, they include longer exposure times. At higher pressures, except if you want to do something else and ask for dispensation, it is heliox which is normally used for compressed gas work, but not yet tried in actual tunneling operations.

Maximum exposure times

Like in diving, we presently have a maximum exposure time per day under pressure for air breathing: 6 hours per day under increased pressure, including decompression time. If decompression is on oxygen you work more, because decompression is shorter.

Trimix in tunneling

About using trimix in tunneling, I have been involved in a full evaluation of trimix operations for the transchannel project. This was a feasibility study made because the pressure could reach 10 bar. At the end of the day the size of the machines and the zone where compressed-air ground was encountered was very short despite the 50 kilometres length of the tunnel. And it was decided that if a breakdown or an inspection was needed in the area with high pressure—which was about 3 or 4 kilometres maximum in the 50 kilometres of the project—they would treat the ground. And that was what they did. They decided on no compressed gas work of any sort. They removed the small "air locks" which were installed on the machines, and they treated the ground by freezing several times. So in that project saturation with transportation, transfer under pressure, habitats and everything like that, were evaluated only as feasibility studies.

Oxygen decompression

Oxygen decompression is recommended but it is not compulsory. The operator can decide whether he wants to use air or oxygen decompression. When you are on oxygen decompression you have stops at 0.9 and 0.6 bar only; there is no stop at 0.3 bar, that is useless, completely useless. Oxygen decompression times are summarized in Figure 1.

What is the experience with the oxygen tables? There have been 3 large operations using oxygen decompression.

One was in Berlin with about 300 exposures in the range of 3 to 3.3 bar. It is a limited number. There was 1 case of mild bends during the operation.

In Sydney they started from the beginning using oxygen and now they have accumulated probably more than 5,000 exposures in Sydney. I don't have exact figures so I have not

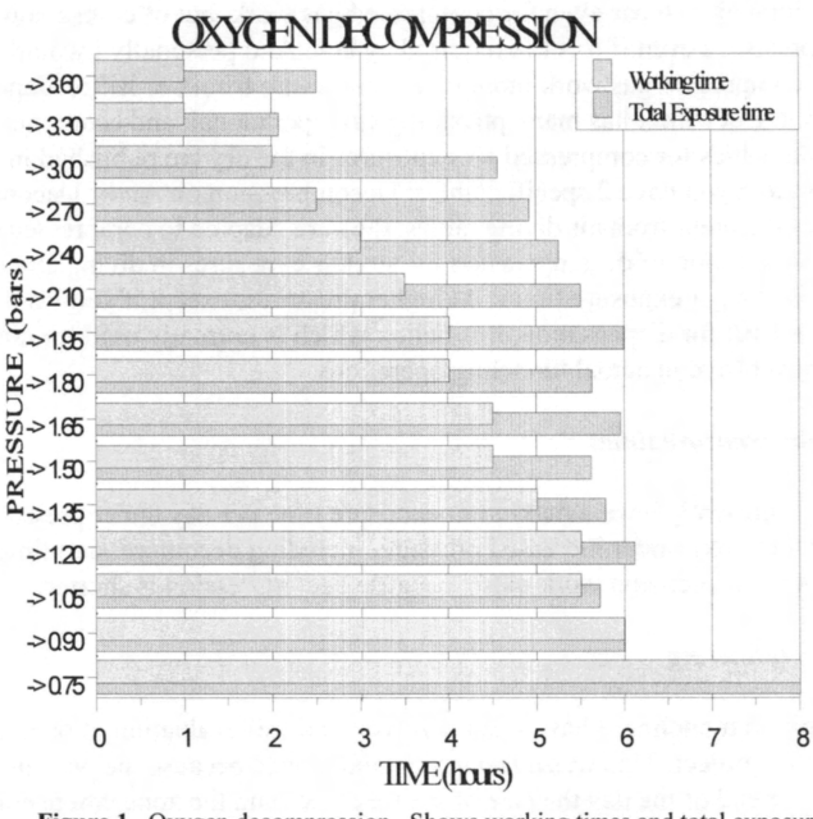

Figure 1. Oxygen decompression. Shows working times and total exposure times using oxygen decompression, based on 1990/1992 French regulations.

included them here. I spoke with them a few days ago and they have been doing a lot in the range of 2.5 to 3.0 bar. And they had 1 case of bends-only DCI.

In Lyon, those who were at the EUBS meeting in BLED may remember we discussed not using oxygen on that project. They did not want to use it although they had all the installation. Since that time they had a major failure in the cutting wheel and they had to go in shifts with back-to-back compressed air exposures at 2.7 bar for more than a month on 24 hours a day shift works. And they made about 4,000 exposures in that period of time and they immediately went to oxygen decompression. Now they have a lot of experience on oxygen decompression and they had only 1 case of mild bends.

Total number of reported cases of mild DCI is 3,which is a very small number. The pressure range where oxygen decompression has been used extensively is 2.4 to 3.3 bar with exposure duration in the range between 1.5 to 3.0 hours, depending on the pressure.

Emergency recompression procedures

Emergency recompression schedules for compressed gas or compressed air are the same as for diving. There is no difference in treating DCI cases whether they have been produced by diving or by compressed air. It is only the clinical symptoms that direct the treatment. According to the French regulation, access to the chamber should be less than 1 hour, and the chamber must be on site when pressure of exposure is more than 1.8 bar.

This requires a short comment. Of the few cases of decompression sickness on air decompression (in the range of 30 to 40 cases) only one showed symptoms on site. All but that one happened when the workers were back at home, often during the night following the exposure. In many cities in France we have hyperbaric facilities in the hospitals. There is always a decision to be made, where should these people be directed—back to the site or directly to the hospital? Most of the policies are to go directly to the hospital. Of course it has been prepared in advance. It is the same in Sydney. In Sydney they have a chamber on site but there is a hospital with a chamber 20 minutes away from the site. And I think the only case they had was not recompressed on site but was transferred to the hospital directly because it is very close. So the chamber may be on site in case you have something on site. But when people are at home or symptoms mild, you have to decide which way is the best. And it depends on the town and the type of chamber in the hospital. The availability of the chamber is a factor, so there may be no formal obligation. It is the liability of the employer to be able to recompress a victim of DCI in less than 1 hour from the discovery of the symptoms, and he should organize the things the way he thinks is best.

There is no requirement for a doctor on site at any time. But a competent medical practitioner must be on call at any time, in particular after the interventions. If a job is that dangerous that you need a doctor, the method must be changed. It is not possible to consider an operation to be safe when you need a doctor on site. I want to be slightly provocative anyway, and I think I am a bit successful. Anyhow, the emergency recompression tables are the same as described above for divers. When the chamber is on site no doctor is required to start the recompression. But, of course, being on call he may decide to come.

Most of the cases reported have been directly treated in the hospital due to the situation, and the doctor never had to come on site (one case only was treated on site).

Medical fitness

In France the legislation stipulates that only the occupational doctor of the company can sign the fitness to work. Anybody going to work has a "fitness to work certificate." When the working conditions include exposure to pressure then the same doctor signs the certificate after he has carried out specific checks according to legal recommendations. If he is not competent in hyperbaric medicine, it is normal practice for him to obtain a fitness assessment from a specialist in hyperbaric medicine. Except when the occupational doctor is the hyperbaric specialist, the final decision is from the occupational physician who is in contact with the employer and the actual working conditions of the exposed personnel.

The reason for this organization is the fact that on site there may be other types of exposures. The only one who knows about the exposures (including radioactive substances, toxic products, risks of falling, etc., is the occupational practitioner of the company; he makes the decision for the worker's ability to work. Therefore the ability to sign the permit to work, as far as medical fitness is concerned, is only the responsibility of the occupational doctor of the company. When there is pressure exposure, he is backed up by a hyperbaric specialist according to a series of recommendations included in the law. This may look special but this is a general way that occupational medicine is taken care of in France. There are no exceptions for diving or compressed air work.

There is a yearly medical fitness assessment up to 40 years of age, and every 6 months after 40. There is no age limit for continuing to practice, but you cannot start working in compressed air after 50. For those who started earlier, it is only the medical fitness that can stop you, or retirement or an accident; then it is a medical decision, never an age limit. Because you have people at 30 who should not go under pressure any more and other ones at 60 who can still do it.

Training

Anybody being exposed to pressure in France needs a formal training certificate. Of course if he is a diver, if he is a compressed air worker, if he is a medical attendant for HBO, it is not the same certification. But they are all of the same shape, like a driving license for heavy trucks, motor cycles, or cars, you have the same license with different stamps. It is the same certificate for all that is called "Certificat d'Aptitude à l'Hyperbarie" (C.A.H.) and there are 4 different categories:

- Commercial industrial divers (Section A)
- Divers involved in other types of underwater activities at work like media, diving instructors, archaeologist, scientists, all these guys who have another job, but in that job they dive, mostly with scuba (Section B).
- HBO attendant personnel, including the doctors (Section C)
- Industrial compressed gas workers (Section D).

For each category you have various pressure levels (Class 1, 2, or 3). For compressed gas works you have a pressure level to 1.2 bar for which the training is simplified. Then for 1.2 to 4.0 bar you have another set of training. From 4.0 to 6.0 bar you have yet another training.

And for access to more than 6.0 bar (it is necessarily on mixed gas breathing) there is another set of training.

Table I below shows a box with lines for the specialties and columns for the pressures. Each certificate has a letter for the qualification. For example the commercial divers have the letter A, the compressed gas workers have the letter D. And then there is a number for the classes of pressure. The qualifications are defined for all the categories of personnel exposed to pressure; these certificates can be obtained in various training agencies which need a formal agreement from the Ministry of Labor.

Presently for compressed gas work (in fact it is compressed air work only because it is limited to 4.0 bar at this stage for the training agencies). There are 3 approved training agencies. There is the national diving school in Marseilles (INPP), my own organization (JCLP Hyperbarie) and a manufacturer of chambers (Comex-Pro) who sometimes sells air locks for TBM and got organized to be able to train people for using the air locks they have produced.

Table I. Training certificates for hyperbaric exposure (CAH) in France.

Pressure (bar)		**0 to 1.2 bar**	**0 to 4 bars**	**4 to 6 bars**	**> 6 bars**
Activities		**Sub-class 1A**	**Class I, II or III**	**Class II or III**	**Class III**
With immersion	**Industrial divers**	**NA**	**A**	**A**	**A**
	Other divers	**B* or A**	**B* or A**	**B or A**	**B or A**
Without immersion	**Medical personnel**	**NA**	**C* or A, B**	**C* or A, B**	**C or A, B**
	Compressed gas workers	**D or A, B**	**D* or A, B**	**D or A, B**	**D or A, B**

NA=Non applicable; * = Authorized Employer; A, B, C, D = Corresponding necessary section

Lock operators and compressed air operations managers are very specific positions that are defined by law. Any hyperbaric operation should be directed by an operations manager. There is no special certification, but the employer is responsible of the selection of the personnel; his personal liability may be involved, so he should be very careful in designating a competent hyperbaric operations manager. The situation is the same for lock operators.

In practice, I train groups of people for a given site. For the pressure up to 4 bar, the training of the exposed personnel lasts four full days, including practical operation of the air lock inside. For the compressed air operations managers and lock operators I generally use 2 more days.

For emergency recompression chamber operators we use air lock operators with one extra day of training, including a course with the doctor just to make sure they understand the Type 1 and Type 2 DCI and the two different tables they have to use. Being already air lock operators the manipulation of the emergency chamber is not different.

Paramedics do not exist in France. You must be a doctor or you are first aid. There is nothing in between by law. If you do things that are close to doctors you may be liable for practice of medicine without the certification. So there is no paramedic, that does not exist. You may use nurses from hospitals.

For doctors there are 2 different levels. Medical fitness assessment of exposed personnel is the responsibility of the occupational doctor and the hyperbaric specialist. The latter one may have graduated from one of the universities with a diploma course in hyperbaric medicine.

To enter the chamber whether for recompression or to go to the cutter head, even the doctor needs the CAH certificate, but this time it is the letter C. Because this is a medical action it is done under the CAH that covers hyperbaric medicine. Plus of course medical fitness, which also applies also to doctors.

National specialities

And last, French specialties. We have good ones, as you probably know, but I shall not use champagne because you know the bubbles of champagne are carbon dioxide and this has nothing to do with decompression sickness, and in addition carbon dioxide does not following Henry's law very well. So this is the worst example that you can use to explain decompression sickness. You should never use champagne to explain decompression sickness. When you want trainees to visualize decompression sickness, use heated water: When you heat water, micro bubbles are formed due to the reduction of solubility of nitrogen in water. This is very close to "decompression sickness" bubbles, you see micro bubbles; they are not floating

Outside champagne, I told you that there have been about 30 or 40 projects involving compressed air under this 1990 regulation. Some in foreign countries, but most of them under the same principles.

At this stage doctors have not reported cases of bone necrosis, but this is only 10 years old. Therefore we still need to be very careful. Most of the compressed air works are in relation to TBMs. Personnel are mostly exposed only occasionally. This might be important when we consider "acclimatization." Eventually they perform heavy repairs, cutter head modifications, or removing big boulders. In Berlin, for example, there was almost 2 weeks of compressed air work on shifts, at 3.0 bar, to remove a boulder that got under the skirt of the machine. They had to cut the damaged part, then to weld a new piece to replace the removed section. This meant mechanics, burning, welding, in a very difficult position down on the bottom of the cutter head.

The French "specialty" is to have a single regulation for all types of exposure to pressure. I think that is an important point. Single certification with various options, for all the sort of things that we have discussed.

This is what I wanted to tell you about French specialties. If you want more details on the tables or on the safety rules that we use for welding and burning, I should be able to discuss them later.

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V.
DUTCH EXPERIENCE IN DIVING AND COMPRESSED AIR WORK

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Introduction

This paper presents a sample of Dutch experience. It should be appropriate for me to talk about my own experience, which covers most of the history of ancient to modern diving, since I have been active in this field for more than 30 years. I started diving in 1966 in the Navy, in a clumsy diving suit with a copper helmet.

Back then we also had a self-contained underwater apparatus that also looks rather clumsy nowadays, but we thought it was very nice. And when I started there were the ideas of Cousteau, thinking about underwater habitats and working under water, living there for months. And there I was in the Navy, only diving up to 50 metres (msw) on air. That was our diving limit in the Netherlands, not 60 but 50 msw. This made me think what I could do to do some useful research, seeing this and visiting Sealab at the time in the United States, and still having to dive with a copper helmet.

However, I was lucky because we got a new chamber installed in 1967 at the Diving Medical Center of our navy. On the bottom there was a wet pot and that made me think about the effects of going under water.

Because at that time, most of the diving research was done in dry chambers and they thought that going under pressure in a dry chamber was really diving, which it is not. This simple thought led me to investigate the effects of the hydrostatic pressure gradients on a diver, particularly with a mixed gas diving apparatus, which we developed at that time.

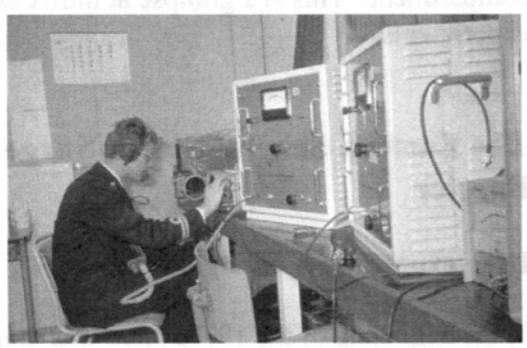

Figure 1. A long time ago (1967) in the Navy.

Figure 1 shows me, a long time ago, sitting behind old-fashioned measuring equipment. Figure 2 shows my assistant in the chamber with a diver all hooked up with pressure transducers and flow transducers and whatever, ready to go underwater so we could do measurements on the respiratory mechanics of diver and diving apparatus, on which I did my Ph.D. thesis at that time (Sterk, 1970; 1973). It was a different approach. Nowadays it is more common to do immersed experiments, but people also tend to go back to the measurements in the dry environment. I think every 30 or 40 years you have to reinvent the wheel again because what was done 40 years ago is readily forgotten.

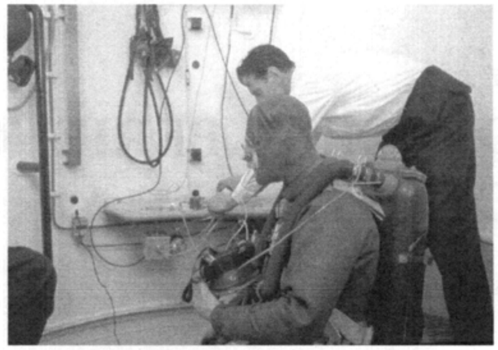

Figure 2. My assistant and a diver inside the compression chamber.

Nitrox saturation: The Unterwasserlabor Helgoland

During my time in the Navy I also got into contact with the Unterwasserlabor Helgoland, in which we made nitrox saturation dives at the bottom of the sea. In Figure 3 you see it at the shipyard Baltika, showing the entrance underneath. It is ready to be lifted into the water and towed away to its location in the East Sea.

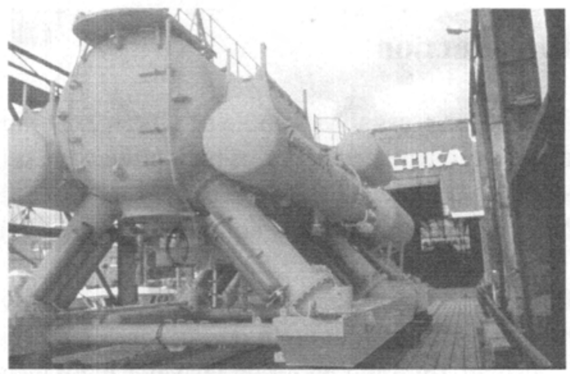

Figure 3. Underwater Laboratory Helgoland at the wharf.

Figure 4 shows a diver coming up. We had a marvelous time and we experienced the effects of nitrogen saturation. I stayed there twice. Above the entrance was the wet compartment with a very nice hot shower. The second compartment contained a place for research, a small kitchen, and a toilet. This toilet was the most complicated equipment inside the habitat. You had to operate it properly. If you didn't, the shit would hit the ceiling, literally. So I was very well instructed, I can assure you. Cleaning was done on a daily basis to prevent contamination in the closed atmosphere. I took my measuring equipment down during the two separate saturation dives I made in it, to do some measurements on divers in the water. The third compartment contained communication and atmosphere analyzing equipment as well as some bunks to sleep in. The final decompression was carried out in this compartment. This is a glimpse at nitrox saturation experiments.

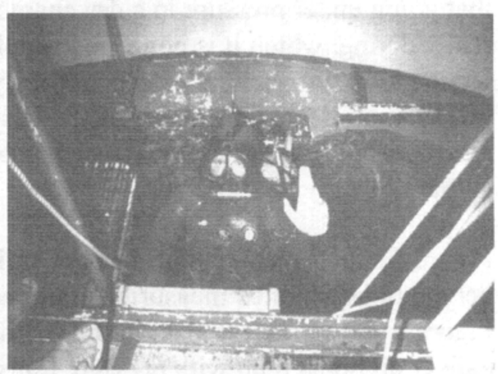

Figure 4. Diver at entrance of habitat Helgoland.

The Eastern Scheldt Storm Surge Barrier

Long exposure air diving tables

In the beginning of the 1970s there was more work coming up and I was about to leave the Navy. A flood in 1953 caused all this, but it took about 25 years before our government was ready to build a storm surge barrier that would protect the people living behind it. The construction of this barrier lasted from 1978 until 1986. But before these dams could be constructed we had to do some subsea soil investigation in the Eastern Scheldt. That was done with a submersible system, starting in 1978. We used a dry diving bell connected to a hydraulic instrument, a base plate with a drilling machine. With this we could take samples from the sea floor to about 70 msw depth or so, to enable the engineers in their calculations for what kind of foundation was needed. From my experience in the Unterwasserlabor Helgoland as well as from my diving experiments at the Navy, I had found out that, for instance, the Royal Navy air diving Table 11 (which we were using during my time in the Navy), was not very good for the deeper and /or longer dives. During my experiments for the Navy we had quite a number of complaints about niggles, some bends, and whatever. At that time, somewhere around the end of the 1960's, I decided to put in some oxygen and a miracle happened—there were no more complaints.

Now for this drilling operation we needed also some very long tables for 4 hours duration at up to 30 msw and the old Dutch tables were not very good for that. So I had to develop some long exposure diving tables. The diving bell could be connected to a chamber located on a barge, so the decompression could be done there by a transfer under pressure. But we still had this old pamphlet from the Ministry of Labor called "Guidelines for safe diving." I can assure you this would not have been very safe. So I came up with some long exposure tables using oxygen from 12 metres on in steps of 3 metres to the surface. I disagree with Mr. Le Péchon that giving oxygen at 3 metres doesn't make any sense. It does. And it makes your total CPTD (OTU) quite a bit lower. As you can see for this dive to 30 msw for 240 minutes (Figure 5), we have—even with oxygen—a total decompression time of about 260 minutes, 252 to be exact, and a total CPTD for dive and decompression of over 500 which we later found out to be too much. But at that time we were quite successful in using these tables as far as the bends incidence rate was concerned. I was then asked to prepare tables for other operations, such as underwater repairs, at the Eastern Scheldt.

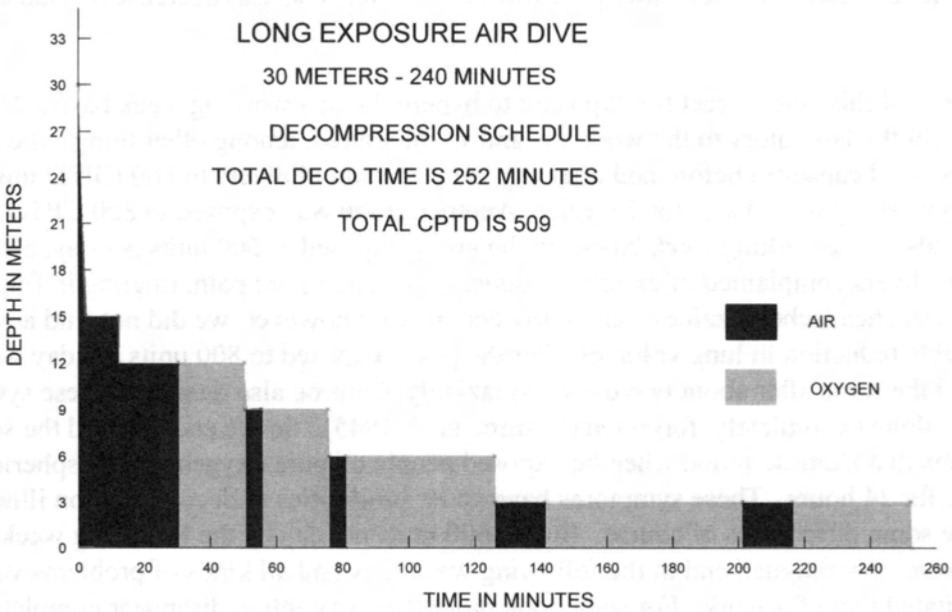

Figure 5. Long exposure air table used during Eastern Scheldt project.

special ship was built for putting big foundation mats on the bottom of the sea. A robot was constructed to inspect these mats for damage after placement on the sea floor. The engineers, too optimistic as usual, thought that the whole operation could be done without human interference. Well, it can't always be that way. We had to do some construction for repairs and for that we used the dry bell. It was put on top of a habitat and then it could be placed over a damaged area of a mat on the bottom of the sea to do the necessary repairs. To keep the water out of the habitat air pressure was raised to bottom water pressure and the divers could work in the dry. This work needed quite long exposure times of over 4 hours. To enable this I further developed long exposure air diving decompression tables using oxygen. What it shows you is that we were talking about diving but in fact this is compressed air work. That was the long exposure tables but then some other things came up.

Enriched air nitrox

There were the large pillars built in specially designed docks. After building these huge things, the dock was flooded and they had to be lifted by a special ship, the *Ostrea*. Once these pillars were lifted, the divers had to go underneath to remove metal plates before the *Ostrea* could ship them to the required location. This involved quite a bit of diving and was a dangerous job as well because if the ship didn't work properly, the divers would be flattened. If they had some problem with the diving equipment they had to swim out from underneath the pillar, which is quite huge, before they could go up to the surface. Therefore we decided to go into enriched air nitrox diving to avoid decompression stops as the working depth was up to 20 msw. And that brought us to another question, "What are the oxygen limits?"

At that time we only had Lambertsen's data, which you all know, the CNS limits at the higher oxygen pressures and the pulmonary limits which occur at a much lower level. For the pulmonary limits it was said that 615 CPTD (Cumulative Pulmonary Toxicity Dose) would be allowable because it would only give you a 2% (it was 4%. Ed) decrease of vital capacity.

I wondered if this was correct for exposure to hyperoxia on a working week basis. Therefore we brought the laboratory to the work site and we measured, among other things, the lung volumes (vital capacity) before and after exposing a group of divers to 600 CPTD units per day on a working week basis for 2 weeks. Another group was exposed to 800 CPTD units per day, also on a working week basis. In the group exposed to 600 units per day, after one week the divers complained of extreme fatigue, muscle and joint pain, tingling in fingers and toes, nausea, headache, dizziness, and retro sternal pain; however, we did not find any measurable reduction in lung volumes. For the group exposed to 800 units per day we observed the same after about two days. Amazingly, Comroe also described these symptoms in 1945, almost completely forgotten (Comroe et al, 1945). So we encountered the same symptoms that Comroe found when he exposed people on pure oxygen at atmospheric pressure for 24 hours. These symptoms have some similarities to decompression illness; there are some differences of course. But on 600 units per day by the following weekend the divers were very fatigued and in the following week they had all kinds of problems which incapacitated them for work. For some took more than a month to disappear completely.

So based on these findings and Lambertsen's data, we set the oxygen limits at 1.5 bar during the dive as far as CNS toxicity is concerned and then for the CPTD, on a working week basis, we allowed 450 CPTD per day with a maximum of 2,500 for one week or 4,500 for two weeks. If it was exceeded in any case, the diver was out for diving for at least one week. And fortunately this worked. [Further developments based on these data are covered in Chapter IX by Hamilton.]

The offshore industry

Surface decompression tables

About the same time the offshore industry started up, and in Holland we do have offshore diving. We have gas, we have some oil. In the early 1980's the offshore diving was, I must say, rather tricky. "Cowboy" stories all around. People getting killed, etc. So that was a new challenge for me because divers of Dutch diving companies had to go down for cleaning and inspection of platforms and whatever. If you look at the air-water interface on a platform, if the sea is a little bit rough it is not always easy to climb out of the water, go to the top, and have your surface decompression there. That could mean a lot of time between leaving the last short stop in the water and going for the first stop in the chamber.

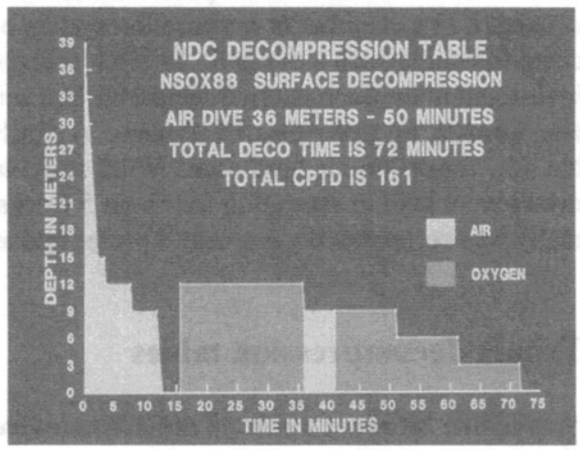

Figure 6. NDC surface decompression table.

During the development of my tables, by Doppler measurements I found that the surface interval, reaching the surface and up to the first stop in the chamber, should be no longer than about 3 minutes or bubbles start to occur. That is pretty tight. Figure 6 is an example of my surface decompression table.

Wet bell tables

Another method of course is to use a wet bell. Since this bell does not have to hold pressure it can be very light, and it needs a very light crane to get it out of the water; it is easy to handle. It can be placed on any structure, ship, platform, or whatever. For this, I developed special wet bell decompression tables (Figure 7) again using oxygen. The divers decompress in the bell, at the ambient pressure.

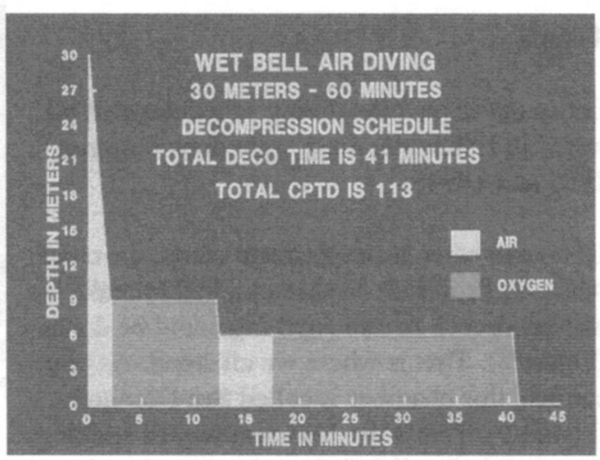

Figure 7. Special wet bell tables for North Sea conditions.

And for these wet bell tables for North Sea conditions, when there is any significant swell, then indeed I have the last stop at 6 msw. But that is only for offshore diving, not compressed air work, but diving.

This period, the Eastern Scheldt experience, and the offshore experience, provided enough data as feedback to refine the computational model. These were put into the Netherlands Diving Center diving tables in 1988. They are used now by commercial diving companies in Holland, inshore as well as offshore.

Saturation and TUP

Now I come to transfer under pressure and saturation diving. We have a dry bell and can connect it to a chamber or a saturation system on board a ship. But you need a much larger crane to handle such a dry bell. In 1981, based on experience with the subsea oil investigation on the Eastern Scheldt, we had some drilling operations in the Strait of Belle Isle, Canada, up to depths of 110 msw. A similar system as in the Eastern Scheldt was used but now for drilling in hard rock. Work shifts lasted as long as 8 hours, and 3 teams of 2 divers were kept in saturation for about 5 weeks. Here we were talking about divers, but it really was compressed gas work. I prefer that term.

Trimix decompression tables

Now a little bit about trimix. Trimix is comvered in more detail in Chapter XII. Trimix was already in use by Dutch diving companies, particularly in the Middle East and later in the Far East at depths between 50 and 100 msw. We started in the beginning of the 1980s. And then at that time the simple solution for use in the Middle East was pumping up the system to 50 msw on air, and then just adding helium to go any deeper. While not a very elegant way to do it, it was practical and easy. And at least it prevented nitrogen narcosis. We all know Martini's law. I don't like drunken divers or compressed air workers in my crew. "Night diving" is okay, but not during work.

Compressed air work

Trimix

Let us cover next the diving schedules that we tested in Hakodate; these were done between 1989 and 1994.

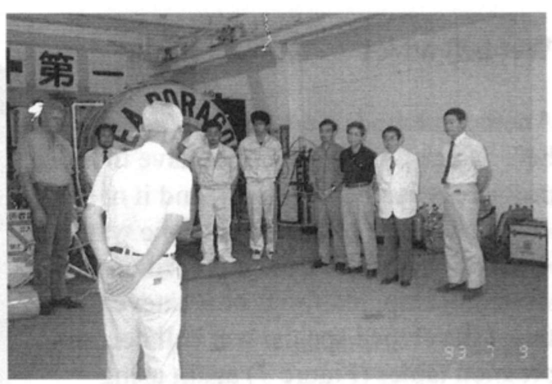

Figure 8. Introductory speech of Prof. Nashimoto.

Of course when an experiment starts, the chief, who was Professor Nashimoto, had to make his official speech before anything could be done (Figure 8). That is where we all stood. As you can see, this chamber is called Sea Doragon (Figure 9). That's the Japanese way of spelling "dragon" in English. It is a nice chamber that goes up to 70 or 75 msw if I remember correctly.

We did several tests, including arithmetic testing and some ergometry testing. In fact these tables were to be designed for light to moderate work, because the engineers told us that in future jobs most of the work would be done by robots, and human intervention would only be necessary for inspection and a little bit of maintenance. It turned out to be a bit different. After trimix exposure and decompression, doppler monitoring was done, and as well as echo cardiography.

Figure 9. Start of experiment in compression chamber "Sea Doragon" at Hakodate, Japan.

In 1995, with the construction of the Meiko West Bridge in Nagoya, Japan, came deep caisson work in which we could test our tables during a real operation. But first we did some more testing at 45 msw, which was thought to be the deepest depth for this caisson work. Professor Nashimoto has covered some of this. I only want to show you a picture of this little lady (Figure 10), a skilled caterpillar driver and, although small, one who handles huge machines very well. She was excellent at handling the digging machines inside the caisson.

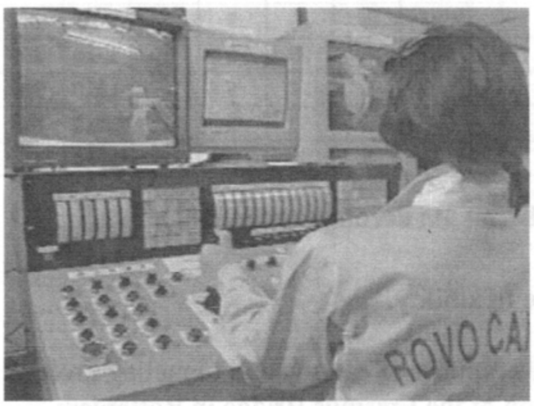

Figure 10. Lady operator at surface.

Figure 11. Robot excavator inside the caisson.

Figure 11 shows a picture of the shovels inside the caisson with the 3-D camera to provide the operator at the surface with the necessary visual information.

After the experiments we had real night diving, of course, in a wet environment but not submerged completely, in a Japanese hot spring. We had a floating tray with cool glasses of excellent Japanese beer.

Caisson decompression tables

Then in 1993 after the Oxford symposium in 1992, I also developed some caisson tables using oxygen (DCD caisson tables) because the old 1905 Dutch caisson law, which has been in force quite a long time—too long—was really dangerous. They just about halved the pressure, stayed there quite some time, and went straight to the surface. Well, it was devastating. Later we got dispensation to use other tables. Royal Navy 11 tables were used, as well as some Blackpool tables. But they were not very satisfactory. Based on experience in the Eastern Scheldt as well as offshore and with some caisson work, we came up with our own caisson tables. Figure 12 shows is how the DCD caisson table looks. We start oxygen at 1.2 atmospheres and then go down to 0.3 and we keep books of the oxygen exposure of course. So the maximum time on 30 msw or 3 bar is 210 minutes. We don't have a rule that we are only allowed 3 hours but the golden rule is that the maximum time under pressure, exposure, and decompression time is 8 hours. So it gives us some flexibility.

Decompressie-tabellen voor het werken onder overdruk (caisson tabellen). Drukken zijn weergeven in BAR overdruk, tijden in minuten en tienden van minuten.
MAXIMALE WERKDRUK IS **3.0 BAR.**
Opkomstsnelheid is maximaal 1 bar/minuut.
De stoptijd gaat in na aankomst op de betreffende stop.
HERHALINGS-INTERVAL IS 16 UUR.

Copyright dadcodat 1993.
Code: cox16

tijd op druk (min.)	tijd tot 1ste stop (min.)	Stops: overdruk in BAR								totale deco tijd (min.)	totaal UPTD
		1.5 lucht	1.2 oxy	0.9 lucht	0.9 oxy	0.6 lucht	0.6 oxy	0.3 lucht	0.3 oxy		
7	3.0	GEEN STOPS								3.0	
30	2.1				5	-	5	-	5	18.0	51
60	1.8		10	-	10	5	-	-	20	48.0	125
90	1.8		10	-	10	5	20	5	20	73.0	185
120	1.8		20	5	20	5	20	5	25	103.0	266
150	1.5	7	20	5	20	5	20	5	45	130.0	318
180	1.5	11	20	5	20	5	30	5	60	159.0	381
210	1.5	13	20	5	20	5	45	15	60	186.0	432

Figure 12. Dutch DCD caisson decompression table.

The DCD caisson tables were used successfully in a number of caisson and tunneling projects by Dutch companies, for instance in the construction of the Erasmus Bridge in Rotterdam in 1994-95.

In Holland we have a somewhat different legal system compared to other countries. For offshore diving it is all pretty well regulated, but for inshore compressed air work it is a little bit different. For inshore it is more or less free, that is to say that in advance you have to make a risk analysis and the people of the Ministry of Labor will just monitor it. If something goes wrong, they will get you. If some of the colleagues specialized in occupational health will comment at this moment, please do so. I am looking at Dr. van der Putten, of course, because he knows much more about the inshore diving regulations than I do.

In Holland we use a different kind of digging. In Japan you have seen the digging machines. In Holland we use water. We fight water but we also use it. We use water cannons to make a solution of soil and water and just pump it out (Figure 13). These guys love to play with the water and it makes a hell of lot of noise, that's for sure.

We also did some tunneling. Figure 14 shows a tunneling project in Portugal (1996-97). It had a diameter of 1.6 metres, which is very narrow, I can assure you. The control room was not too bad but if you look inside where these big Dutch guys were sitting or this type of entrance to the air lock, it was very cramped. It was very heavy work and, of course, they did not install any oxygen so we had to use air tables, unfortunately. But we only had one case of decompression sickness. It was a German engineer who was with this project and had to fly back to Germany and he didn't want to wait. When he returned I was told that he was treated, I don't know where and I don't know the outcome. But that is how it goes sometimes. It is often difficult to get people to wait before traveling by air after compressed air work.


Figure 13. Water cannon for ground removal inside a caisson.

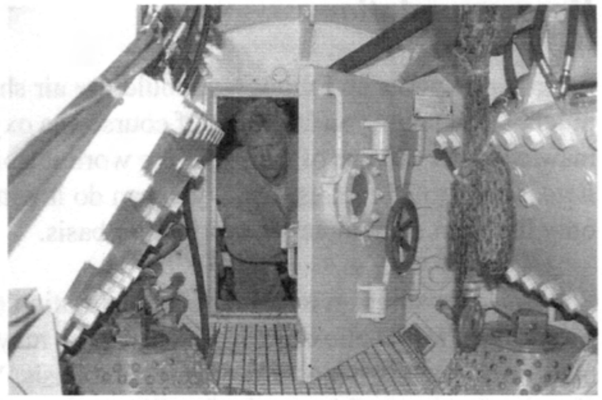
Figure 14. Entrance of small air lock; tunneling project in Portugal.

Then we also have the sluice door foundation in 1997 where again water jets were used to excavate the caisson. In fact this method of getting rid of sand or mud can also be done automatically. However here I have to make a statement based on our experience. It always seems that engineers tend to underestimate the necessity for human intervention. They come up with it too late. This was also the case in the Eastern Scheldt. They thought they could do it all by robots and big ships and whatever, and it turned out not to be so. Particularly in the last couple of years of this project we had about 75 divers working day and night to get the job done. And then we had to arrange many things. We had to educate people, we had to teach people, we had to train some divers to become paramedics. We used paramedics. We are using them offshore, we are using them inshore. We had to call on different diving companies to get all these divers together and work as a team. Not only at the Eastern Scheldt, we have seen it in Portugal, we've seen it everywhere. And I am very concerned about this because if there is a disaster coming up, then the engineers are coming to the diving people. And they want a solution, which is not always possible or very easy.

Summary of Dutch experience

In summary we have quite a lot of experience. Particularly in the diving things and in saturation and caisson work, tunneling a little bit, decompression table development extensively.

Finally a statement of Bill Hamilton about decompression tables, which I love, made in 1986: "I don't think a decompression table should even be printed in typeset form, let alone cast in concrete or engraved in brass. I think it should be a computer print out in disappearing ink, so that after a year or two you need a new one, because we are learning constantly on this subject."

That's why we put the NDC tables in a loose leaf binder. With all respect for the French book, it has the danger in it of becoming a bible, as with the U.S. Navy tables. And we should avoid that; do not make it into law.

Recommendations

From our experience I think we should use air shallower than 30 msw, not 40 msw, 40 is too much. I will show you later on. Of course use oxygen during decompression. For over 30 msw consider the use of trimix; if the work is going far beyond that depth, it can be useful. If it goes only to 35 metres, O.K., you can do it with air, it is not a sharp boundary. But that is only for short exposures on an irregular basis.

For long exposures on a regular basis saturation technique should be considered, and then it should be I think heliox or trimix saturation, maybe nitrox. We should use it deeper than 30 msw only for long exposures on a regular basis. You can't leave people for 4 weeks inside a chamber having nothing to do. It will become a disaster. In that case relatively short exposures on trimix should be preferred; more about this later.

This is what I wish, that the owl of wisdom will lead us to solutions that make hyperbaric work even more safe and successful.

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DISCUSSION AFTER DR. STERK'S DUTCH EXPERIENCE

Dr. Ben van der Putten: It is the law in Holland that every company make a risk evaluation of every project undertaken. And when they have a risk evaluation report, they have to take measures to make the work as safe as possible. So there is no law that says you have to do it like this or you have to do it like that, but the labor inspector sits in his chair and waits for things to go wrong. When things go wrong, they can find you.

Dr. Walter Sterk: O.K., thank you. Well, that also goes for the tables, but usually the inspector of labor will ask in advance what kind of tables you are going to use. They may ask for some advice and if it is agreed that the tables may be used, they will be, but if something goes wrong, you are in trouble.

Dr. Karl-Peter Faesecke: Just a remark on the rectification of the Dutch caisson law of 1905. It was the only legal paper available when they started on the first Elbe tunnel 90 years ago; and the health qualification standards for the workers on the old Elbe tunnel were taken directly from the Dutch regulations.

Sterk: Ah, poor you.

Faesecke: Well, that was 90 years ago. We may go back to that, taking experience from the Dutch. Natuurlijk heb ik er geen problemen mee om van Nederland te leren.

Mr. Jean-Claude Le Péchon: About the long duration stop at 6 msw. Of course we know about the oxygen toxicity. And the recommendation is, as long as you do not reach about 300 or so units, try to stay deep as long as possible. And when you reach this value, of course reduce the exposure. But you can stay there as long as possible, a few minutes is possible at 3 msw. And in the tables as we have we don't reach these values as UPTD, so we are not concerned. This is the reason. And the other point, the table being "cast in concrete,"they are what we call in France a "narrative," which is the lower level in regulations, and it can be changed in terms of weeks. So it is made for that. And we presently have many ideas on how to improve these tables, and I hope it will come soon. O.K. That's all, thank you.

Faesecke: Let me focus on this. We did it a couple of years ago when we started the deep excursions on the Kiel tunnel, 12, 9, 6, 3. Because breathing oxygen while going 9, 6, 3 msw doesn't make sense, we agreed to have it at 10 and 5 msw. The 5 msw was due to the problems most of the engineering people had with oxygen at 10 msw for all the time; but if you have understood your Haldane there's no need for shallow oxygen stops. You can do it all at 10 meters. But there was the problem of oxygen toxicity. We calculated it and we agreed to spend half of the decompression time at 10 meters and the other half at 5 meters. And that is what we find in our regulations today. But I agree, there is actually no need for going on oxygen at shallow stops. Because it doesn't make sense.

Sterk: It does make sense when you are going to make long exposures.

Faesecke: I was talking about compressed air work for 90 minutes or so.

Sterk: Yes, 90 minutes, but that is short.

Faesecke: So in short diving you could handle it all at 10 msw.

Sterk: Yes, but then we are talking about short exposures and I think this is usually not the case in compressed air work. We have seen it at the Meiko Bridge where we were aiming at exposures of 60 minutes. It turned out to be 2 hours most of the time! Because otherwise you don't have sufficient time to fix the problems that may occur. So in any complicated type of job where you have longer bottom times or exposure times, I think it makes sense to be careful with your oxygen and go as soon as possible to shallower stops. And I think that in the future, the coming 10 or 20 years, we will get more and more deep caisson and tunneling work, particularly in the river delta areas, like Holland, because it is over-populated. That's the same as in Japan, we have to go down to use our limited space. And it will become more complicated. We need longer tables and new techniques. We better be prepared for the future and not only look back and stick to the old things.

Faesecke: That's what we are here for.

VI. NORWEGIAN EXPERIENCE

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Introduction

The previous lecturers are more famous than me, so I think I should just give a word about myself so you know who I am. I am a diving physician working at NUI which is a child of NUTEC; I hope you all know of that institution in Bergen, Norway. I work part time as a Surgeon Commander in the Norwegian Navy and as a consultant in diving medicine at our university hospital. And I am diving physician for the three Norwegian oil companies. Most important, of course, I am the "Norwegian expert" in caisson work. That is very easy because we haven't had any, not at all. But I am, look at me, I am the national expert here with you. Thank you very much for giving me this opportunity; Norway will look to me, and I will be called in.

We have not had any caisson work in the last 34 years. There may be some people who may know something, but I doubt you would have any interest in it even if I did know. So what can I do? I will tell you something about Norwegian diving, because we do some diving in Norway. I think that could be of interest to you, although I cannot share any information regarding compressed air work.

Inshore we have had major pipelines arriving at areas like Kalstø and Kårstø and we have had the turnover of the Alexander Kielland platform. Offshore we have some projects, and all together there is a lot of diving in Norway. I don't think you would call them major projects, but we are doing lots of diving.

National regulations

Inshore diving and compressed air work

Our national regulations for inshore diving and compressed air work (which we don't do) are managed by the Department of Local Administration. They have a Labor Inspectorate where one person is sitting, and that one person likes to sit there. So he swims backwards. In that way, it makes it a little hard to change a regulation. This is not a problem specific to Norway, because when we talk, you know over a beer and so on, this is an international problem in that much of the regulation seems to be handled by too few persons. I think so at least.

We have about 1,200 diving certificates in the inshore diving community, with about 500 of those going for the annual medical examination. We don't know exactly, but there seem to be some 200 or 300 persons diving commercially without spending the money necessary for the annual medical exam. So that will give you an idea about the amount of diving in Norway.

Offshore diving

Offshore diving is handled politically by the Department of Oil and Energy. The inspection is done by the Norwegian Petroleum Directorate on the operational side and by the Norwegian Board of Health for the medical side. About five people all together, very professional and outstanding people, deal with the offshore market, and the communications are very good. I cannot tell you for sure because I could not get an official number, but I believe about 150 Norwegian saturation diving certificates have been issued. And we have three to six Norwegian divers steadily employed. All the rest are contracted in one way or another.

About 50 Norwegian divers work during the season, and this is a major part of their income. But as for offshore diving, manpower wise, this is small in Norway and not an economic factor. While the economy is still rather good in offshore diving, it is declining. But altogether the clients, the oil companies, are willing to pay for such services.

Some years ago two major diving contractors; the Norwegian Stolt-Nielsen and the French Comex, joined and now they are one large company, Stolt-Comex-Seaway.

Rockwater is sharing the market in a joint venture contract that allows them to survive and makes the price acceptable for their part. The diving contractors are large, a lot of employees altogether. They work internationally. They have a stable work force and a high level of proficiency. And important for us, they have a long lasting research and development policy. They are very health and safety oriented. The government, the clients, and the diving contractors focus much more on safety, whereas the public focuses much more on offshore divers' health. The Norwegian public believes that most of the diving problems are concerned with deep diving, those deep divers who go down to several hundred msw. You have seen the numbers, so you can understand that that can't be much of a national problem for us. It is not so very exciting with those divers diving to 20 or 30 or 50 msw; that's not really deep, just a bit more than you do when you scuba dive.

Inshore diving has a pure economy. They are small companies where most divers are self-employed. Roughly ten companies have more than 10 divers employed. We have about eight pressure chambers altogether in the inshore market in Norway. They are hardly able to focus on health and safety. And there is no governmental, client, or internal follow up, or internal control. So there is a huge discrepancy between these two areas of diving in Norway. This may apply for all the nations as well, I don't know.

Medical responsibilities

In offshore diving the medical responsibilities are cared for by the Norwegian Board of Health and the Norwegian Petroleum Directorate. That concerns legislation and control of health factors. The oil companies and the diving contractors are both responsible, together with competent diving physicians, and they work constantly in areas that can be improved. The diving contractors have a duty doctor on call. There is a vessel or platform nurse on each diving site in the offshore diving field. And the divers are trained in advanced first aid.

Concerning inshore diving, we have the Norwegian Labor Inspectorate, which is very much loaded with work. A couple of years ago I visited them and tried to ask them to put more effort on divers. The man I was talking to said, "Listen, how many people die due to diving each year, inshore diving." "Well," I said, "I believe it is some 2 or 3 years ago since the last person died." "Well," he said, "do you know how many people die making those ladders and scaffolds in Norway?" "No," I said. "Fifteen! Fifteen versus zero, and you ask me to put focus on diving?" That is hard; I mean we compete with a lot of other areas that cause more deaths and diseases than diving, so it is hard to get focus on the inshore area. There are two physicians employed by the Labor Inspectorate and only one diving contractor inshore has a diving physician. We have a national duty arrangement for hyperbaric emergencies located at the University Hospital in Bergen. And the local emergency departments provide the divers with general medical emergency treatment. But in reality, there are no local diving doctors available for them.

Depth limits and decompression tables

For offshore diving, there is a maximum of 50 msw using air. You may use any accepted diving tables, but in practical terms oil companies use the so called Norwegian tables, which in reality are metric British Royal Navy tables. For inshore diving, there is no formal limit, but indirectly it is 60 msw on air, due to the fact that you are supposed to use the Norwegian diving tables and they stop at 60 msw.

As for the use of oxygen in decompression, we only use that for surface decompression. There is no in-water oxygen decompression. We use the U.S. Navy tables' in-water decompression stops at 18 to 9 msw and then give surface decompression on oxygen at 12 msw.

Therapeutic regimes

If you have a decompression illness, you are supposed to give surface oxygen and fluids, orally or intravenously. We are among the few nations that still believe in using dexamethasone and dextran for a treatment of neurological DCI. Of course we transport them by air ambulance or helicopter, requiring cabin pressure and all this. For the hospital treatment we have five fixed chambers in Norway and they are usually located outside the hospital. The primary diagnostics are then done at the pressure chamber. We use the U.S. Navy diagnostic form to try to standardize this, but I don't think there is too much standardization on the form so it does not help much.

In hospital treatment for DCI we do the usual stuff. U.S. Navy Table 6, except for AGE; if there is a short latency we still compress to 50 msw (6atm, USN Table 6A). We may use Table 5 in mild decompression illnesses such as skin bends. For any serious DCI we will use either the Comex 30 Table, only available in Bergen, or saturation at 18 msw on heliox if the diver does not respond to the Comex 30 Table.

For repeated treatments, we treat them until clinical normalization and stabilization using Table 5 or the 50 msw table, 3 periods of 30 minutes, once to twice daily.

Medical requirements

Fitness to dive

As a prerequisite for inshore and offshore diving both require an annual medical examination done by authorized diving physicians, each containing the clinical interview and conventional medical examination. We still require annual chest x-rays, but this is to be abandoned this year; hemoglobin and hematocrit are the only blood samples, and ergometry and spirometry.

Our regulations have been changed this year and are harmonized with the U.K. regulations. And I think it is important for anyone who is dealing with regulations for professional divers to try to harmonize with the European Community.

And we require a physical work capacity test which is to be standardized on the first examination and then you have a number of options on how to do it.

Offshore

Offshore we still require a long bone x-ray each 3rd year if you dive deeper than 50 msw or in the 5th year in the 30 to 50 msw zone, a requirement that will be changed this year and will be the decision of the examining doctor.

Doctors doing medical certification for inshore and offshore divers are required to have basic training in diving medicine; a one week course is satisfactory for that. But you need a formal governmental approval. HSE doctors are automatically approved for this purpose in Norway as well.

Offshore there is a high training standard required for an advisory diving physician, of which there are only very few amongst us. Significant practical training and individual evaluation of each applicant is required for the occupational physician giving advice.

There is a formal requirement for duty doctors. Again, individual evaluation, governmental documented training, and practice. The nurse has to be trained in emergency medicine.

Concerning our offshore divers, we require that 80% of the divers have a valid advanced first aid course in addition to the basic safety course which has to be renewed on a periodic basis.

Inshore

Inshore, there is a requirement for an advisory diving physician. You don't need any specific formal qualification or formal governmental approval. The divers do not require any medical training beyond what has been done at the commercial diving training school.

Recompression therapy on site

If you dive inshore, deeper than 24 msw, you need a compression chamber on site except for short inspection dives, and no one has defined "short." If you want to decompress in the water longer than 35 minutes you need a recompression facility on site and that has to be larger than 1.8 metre in diameter.

Offshore, I really haven't read the regulations but it doesn't matter, it is always on site and there is no question about that, it is always available.

Well, as to national specialties, I don't know. We have a facility for hyperbaric lifeboat reception at NUI.

Fatalities

Concerning our fatalities, the last one inshore was in 1994. Offshore was in 1988 or 1989, I am not sure. It was many, many years ago. Concerning decompression sickness, inshore we have three to four each year. And offshore the last one we observed was in 1993. So commercial diving in Norway is a very safe activity. We don't believe it only based on these numbers, but also on the total package of information we get back from the divers as well.

I am sorry I cannot share some more construction work with you but I don't have the knowledge.

DISCUSSION AFTER DR. RISBERG ON NORWEGIAN DIVING

Dr. Karl-Peter Faesecke: Thank you very much. Don't make yourself smaller than you are. There is a reason for your being here. Since the separation line between compressed air work and diving is becoming more and more permeable, we have to put our combined knowledge together. One final question: In Norwegian understanding, is recompression a medical performance under physician's guidance or can any diving supervisor perform a recompression treatment ?

Risberg: Any supervisor can do that if the diving manual tells that you are allowed to do so, because the diving manual has to be approved by the diving physician. He has to sign that he has read it and agrees with it. So the manual will say what shall be done.

Faesecke: Whenever you experience a seizure when doing a treatment you will think differently about these things. But we won't go into that further, we leave that for tomorrow. With our next speaker coming from Munich, you will see that you don't need to live at the seaside to become a diving doctor.

VII.
GERMAN EXPERIENCE

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Introduction

This is a short presentation of German regulations in compressed air work and professional diving, and a brief look at current results of my studies of DCI incidence. Besides these existing regulations a new field of compressed air exposure risks is discussed in Germany. There are more and more therapeutic HBO_2 chambers being started, run by doctors who are not completely familiar with the problems in hyperbaric situations, especially with the risks of personnel exposed repetitively. Because of this we are at work on a new regulation for exposed medical personnel.

In Germany we have a legislated regulation for compressed air work (Druckluftverordnung i.d. F.v. 19.6.1997). We have a regulation for professional divers (Unfallverhütungsvorschrift "Taucherarbeiten" VBG 39). We have regulations for scientists who dive (Sicherheitsregeln für Forschungstaucher ZH 1/540). In addition we have instructions for the treatment of DCI (ZH1/587), instructions for compressed air workers and lock guards, guidelines for welding in compressed air environment, etc. These are listed in more detail at the end of the paper.

Pressure and time limits

Let`s have a brief look on the limits given by the German regulations, as presented in Table I.

Compressed Air Work:	max. pressure 3.6 b (gauge) resp. 36 msw	
	max. bottom time (at 3,6b)	2:00 hours
	max. decompression time	1:56 hours (100% Oxygen)
N.B. regular decompression with 100% Oxygen at 10msw and 5msw levels		
Professional Diving:	max. depth	50 msw
	max. bottom time	20 min
	max. decompression time	25 min
Regulations for mixed gas and new air deco-schedules are being prepared		
Rescue Services:	internal regulations with lower limits between 25 and 30 msw	

Table I. Depth and time limits as given by the German regulations.

In Germany the regular decompression in compressed air work is performed with 100% oxygen breathing at 1.0 bar and 0.5 bar (gauge). German regulations give individual requirements for the exposed as well as general limitations, e.g., in age. You are not allowed to begin compressed air work while you are younger than 18 years and there is a limit of 50 years. This 50 years limit is not for professional divers (Table II).

Legislation in Germany	
Medical Fitness Test (spezielle arbeitsmedizinische Vorsorge G 31 "Überdruck")	
Necessity of medical Examination	
professional Diving before 1 st. exposure	compressed air work before 1 st. exposure
Interval of repetitive examinations	
max 12 months	max 12 months
or: immediatly after DCI or other compression related illnesses resp. other incidents or cleseases	
personell prerequisites	
Age at least 21 years (no limitation for age > 21 years)	Age between 18 and 50 years

Table II. Medical fitness test and age limits.

Medical fitness

We require a medical fitness test every year (Table II), it is bound by law, and it is surveyed by the authorities. Repetitive examinations are asked at least once a year, or if you have a DCI occurrence or suffer from other illness or accident (Table III). Only specialist doctors (occupational medicine plus hyperbaric qualification) are legal to examine divers and compressed air workers.

Medical Examination for compressed air workers and divers (G31)	
Patients history (regarding the specific stress and strain of compressed air work)	
Physical Examination	Hearing Test
ECG	Urine Test
Stress-ECG	Blood Test
Lung-Function-Test	Height and Weight
Chest X-Ray	Exposure Test in the hyperbaric Chamber (if available)
Vision Test	

Table III. Content of medical examination.

Decompression tables

Regarding the very new German decompression tables (legalized in December 1997) we now have a maximum pressure of 3.6 bar (3.0 bar in former regulations), with a maximum bottom time of 2 hours, and a maximum decompression time of 1 hour and 56 minutes in oxygen decompression at a 10 msw level and a 5 msw level. As you can see there is a difference in overall working time in comparison to other countries tables, e.g. English "Blackpool tables." If you sum up bottom- and deco-time you get a maximum of 4 hours. We don't do it the way we heard from the Netherlands that up to the maximum pressure you are allowed to expose a full shift period. For us, the deeper the exposure is, the shorter the maximum bottom time allowed (being aware that in deep and long repetitive exposures the border of saturation in the slow compartments may be hit).

In addition to that, we have calculated the tables with a UPTD of 300 units. More decompression time than 2 hours is not likely, so this is the limit due to oxygen toxicity. If the pressure is lower, the available working time is increased.

So what about the maximum work and decompression schedules in **air dives**? We have an accepted maximum depth of 50 msw, with a maximum bottom time of 20 minutes and a maximum decompression time of 25 minutes. We say that repetitive dives are possible up to 35 minutes of bottom time if you add the diving time of the 2 dives, the sum of dive 1 and 2. We have no regulations yet for mixed gas, but they are being prepared.

You know the current German tables. The black numbers are meant for the first dive. Under the red line, this is for the repetitive dive and the red figures should not be reached, they are only for emergency cases. In the not-yet-legalized new table, you see we have the possibility of up to 1 hour of deco time, about 30 minutes of bottom time and in the other example you saw we have 20 minutes of bottom time. So the new tables would have been a benefit for diving contractors. But maybe we find a possibility to deal already with these tables.

These tables have been in existence since 1956 as the so-called "Dräger Tabellen," but I have no information on who calculated them at that time. That is another story to be told. Our new tables for compressed air work have been developed by the DLR (Deutsche Versuchsanstalt für Luft und Raumfahrt), led by Dr. Jürgen Wenzel. The tables have been studied with their own experimental computer model, with data from compressed air work in Munich, with data from compressed air work in Kiel, and data of international diving contractors.

We tried to find a scientific organization in Germany, a university or scientific institute familiar with diving physiology and decompression, to make a study for new diving schedules. But we didn't succeed with this, diving is currently not that important in Germany so we couldn't find any institution that had the capacity to do that. The lookout for safe and modern tables attracted us to the French regulations and we took a lot of the schedules from these "Mesures particulieres de prevention" (which are genuine Comex tables). So for example the philosophy respecting the repetitive dive changed. I don't want to extend this too much, but we are beginning to go one step ahead, to get all the different diving schedules a little bit closer together.

I agree with you, when you say the table alone is not "safe." All the confounding, especially the organization of work and working conditions on a compressed air work site is nearly as important as the table itself.

Oxygen decompression

Now a few ideas about our arguments for oxygen decompression. We have had a lot of experience with oxygen decompression in Germany. Even with the old tables, oxygen decompression was possible, but unfortunately with too short decompression times, so we did not have very good outcomes with these old tables (referring to DCI).

To study oxygen side effects we surveyed more than 20,000 exposures and saw in all these exposures of 135 individuals only 4 cases of myopia due to oxygen breathing. No other oxygen effects could be detected.

The knowledge of the different effects of oxygen is the basis of our new German tables. As there is the effect of a rapid wash out of nitrogen, a significantly higher oxygen concentration in the tissues, this lowers the bubble progression, for example. In addition, when we use oxygen decompression we always offer a system of therapy during regular decompression. Maybe this is another benefit of oxygen decompression. I agree with you, even the low oxygen decompression level at 3 msw or lower, does have some of the mentioned effects. There is no contradiction to the use of 100% oxygen at 1 bar in diving accidents, which shows a good outcome. So in our regulations for first aid and rescue in diving accidents, the use of 100% oxygen breathing at atmospheric pressure is obligatory. We know the benefit of that.

I agree with you, but I didn't want to get into the subject of chemistry and physiology of oxygen. To point out the practical aspects of oxygen schedules I want to present you the results of my current study, evaluating the effect of 100% oxygen breathing according to the new German tables. I studied the data of 6 caisson sites in Berlin. The last site ended recently at the end of March. So these are very new data I haven't worked out completely. So I evaluated 4,500 exposures, and in these exposures 2,883 had to run a decompression. All these decompressions were performed with oxygen. We had a very low rate of DCI, only 5 cases. This is an incidence of 0.18%, an acceptably low rate of DCI.

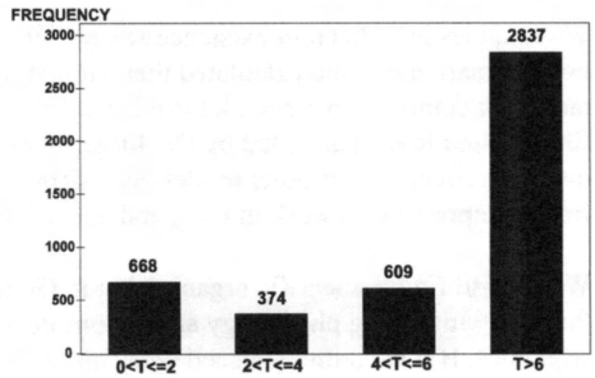

Figure 1. Number of exposures (frequency) against working time (T) in 6 recent caisson sites in Berlin.

In my preceding decompression risk study we reviewed more than 20,000 exposures with an overall incidence of about 2%, with shorter oxygen decompression times. It was varying between 2.2 % and 1.8 % but it was significantly higher than the 0.18 % we calculated in this recent study. So I assume that oxygen breathing has a very clear effect on the prevention of decompression illness in compressed air work.

Figure 1 shows the typical profile of such a site. The majority of working time (T) was between 7 and 8 hours. Most of the exposures were full shift exposures. And in all DCI cases we had full shift exposures.

Figure 2 presents the frequency of the exposures related to the pressure. At all pressures greater than 0.7 bar oxygen decompression was performed. What I wanted to point out with these data from 6 caisson sites is the obvious benefit of sufficient oxygen decompression. So I assume we should go on with the consequent application of oxygen in hyperbaric exposures. The results of our study should encourage other countries to use the advantages of oxygen breathing.

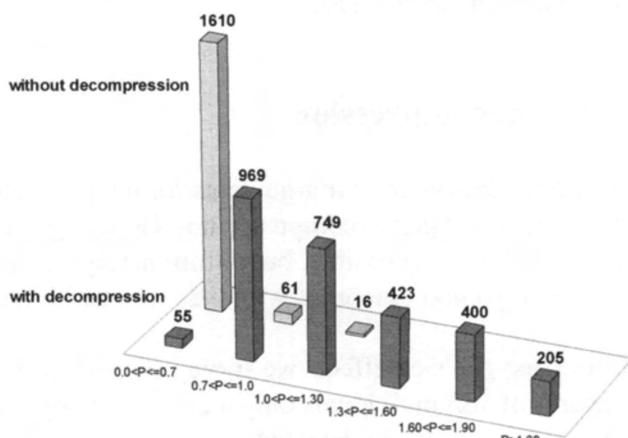

Figure 2. Frequency of exposures related to pressure. The dark columns are the exposures with staged decompression.

Adaptation (acclimation)

I would like to discuss briefly the problem of acclimation or adaptation. A caisson site typically has perfect conditions for the compressed air workers to adapt. Because, beginning with atmospheric pressure, this will increase every day a small amount, which provides a good possibility for acclimation. On the other hand we have sites with relatively constant pressure (e.g., this very site "Elbe Tunnel 4" where we are meeting). The example of this site shows a much higher incidence of DCI, although using these oxygen decompression tables. When workers are not exposed for a few weeks and suddenly exposures of a full shift period to the maximum depth are requested, different problems are encountered.

In advance I want to point out how important it is to have the confounding conditions of compressed air work well organized.

Emergency cases

What we try to do regularly is to think about what is to be done in case of emergency, how to get someone out of the working chamber. You know the working chambers of TBM`s, with small diameters and tiny personnel locks. A lot of problems start when you have to get a severely injured person through the lock.

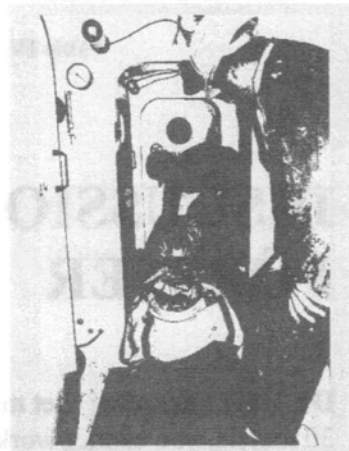

Figure 3. Handling an emergency in an air lock.

The picture in Figure 3 shows you that often the air locks are so short, that you cannot put through a person lying down. And there is no way to change this, no chance to make an airlock any longer after tunneling starts. We found a solution to the problem using a helicopter-adapted vacuum mattress we ordered from the mountain survey ("Bergwacht" in German). With this tool we could make the lying person a little "shorter," a length of 1.5 m inside of the air lock, short enough to pass it through.

Legislation in Germany

With this bundle of compressed air work and diving related regulations and official guidelines in combination with the request of special trained doctors who can deal with modern oxygen decompression tables, there is an acceptably high standard for hyperbaric exposures in Germany (Table IV) The latest German compressed air work risk studies prove the effectiveness of modern oxygen decompression tables. But new techniques will have to be developed in the field of compressed air work deeper than 36 msw. Mixed gas techniques or saturation exposures will have to be taken into consideration. The lowering of DCI significantly beyond 0.5 % is still a challenge for us, especially in the field of tunneling, conventional or with tunnel boring machines. We will go on evaluating the outcome of those exposures.

List of compressed air and diving related regulations and guidelines
Druckluftverordnung i.d.F. v.19.6.1997
UVV Taucherarbeiten (VBG 39) i.d.F.v.1.1.1997

Richtlinien für den Einsatz von Forschungstauchern (ZH 1/540)	
Sicherheitsregeln für Druckluft-Leichttauchgeräte (ZH 1/237)	
Richtlinie für Taucherdruckkammern (ZH 1/539)	
Merkblatt für die Behandlung von Erkrankungen durch Arbeiten in Überdruck (ZH 1/587)	
Spezielle arbeitsmedizinische Vorsorgeuntersuchung G 31 "Überdruck"	
UVV Arbeitsmedizinische Vorsorge (VBG 100)	
Tips für Druckluftarbeiter (Abrufnr. 681)	
Tips "Schweißen und Schneiden in Druckluft" (Abrufnr. 680)	
Regeln für Sicherheit und Gesundheitsschutz bei therapeutisch genutzten Druckkammern (being prepared)	

Table IV. Legislation in Germany concerning hyperbaric work.

DISCUSSION FOLLOWING DR. FÖRSTER

Dr. Karl Faesecke: Let me just make one remark on this problem of short shifts. Working at 30 meters, you cannot work longer than 4 hours. The company pays the man for 8 hours, so what is he going to do for the rest of the time? We are running into this problem, because as Bornstein already said, "No hard work after decompression." And that's exactly what we are doing here, because you can't send them home after 4 hours of work. So they are kept busy with whatever job is around. And we will have to look into that. Should they work before, which isn't too good. Should they work afterwards, and how much, and for how long. I guess we leave that to the discussion tomorrow. I think as a sum up, we have to realize that though men are equal all the world over—any medical student could learn from a Japanese anatomical book, and learn about medicine there—we realize that work tables in diving and compressed air work are so different the world over. If this were really a science, they would all be alike; I mean, doing a heart operation, like a bypass, is the same everywhere, whether you go to South Africa, Argentina, Japan, or wherever. But going under water and taking someone back to the surface, is so different the world over. I just cannot explain that medically. Are these only national peculiarities? Are certain nations more prone to decompression sickness? Or are they too proud to accept findings from other countries? I think there is still a lot of work to be done, to transform this, what we are doing right now, into a real scientific job.

Dr. Walter Sterk: May I add something? Oxygen does have, hyperbaric oxygen that is, does have many more effects than improving inert gas wash out and oxygenation of tissues, also in decompression when silent bubbles are present. Not only the bubbles, but all the things that happen in connection.

Dr. RW Bill Hamilton: Chemical cascades.

Sterk: Right, so it does much more than [replace inert gas].

Mr. Jean-Claude Le Péchon: I think the difference between tables is basically the social acceptability of [DCI] cases. You have countries where fishermen pick up lobsters accepting 10% neurological DCS; they don't know why, and they do nothing about it. And the social acceptability is at that level. In our countries nowadays social acceptability is almost zero. And especially the people running these sort of things don't want to have a decompression sickness case on their job. because it will stop the machine, it will make problems; they don't want any. So the social acceptability has become very, very low. And that makes differences in the tables.

Sterk: That's one point. I agree fully. There's another thing and that is that in too many countries the tables are still in the law. And they are stuck with it. Like in the USA and like in Japan.

Hamilton: One very real reason is, "that's the way we've always done it." That's the "technical" reason for a lot of this stuff. It is tradition. There's one perception of the tradition, the social acceptance of decompression sickness, but that's due to a lot of things. Things can become really ingrained. It is very difficult to change that.

Sterk: There's one other thing. I think that not every job needs the same decompression table. I think we should focus more on particular tables for particular jobs. It depends on the circumstances, it depends on the skills of the divers, it depends even on the management, or on the amount of fluid they are taking in, or whatever; there are many variables. And we should look at every operation, and in fact design special tables for it if necessary.

Faesecke: That reminds me of a paper I put out some years ago where I stated that "we should aim at individual decompression." So if we come up with a collective decompression ratio valid for all the people working, there will be some range of bends like 5 to 2 percent or whatever. If we knew what influence certain factors have on individual decompression it should be possible with that small number of people to introduce individual decompression. If we know that some fellow is especially susceptible or has been working very hard or has been taking too little fluid, we might take him out of work 10 minutes earlier or give him a couple of more minutes of decompression. That must be feasible with modern technology, with a different type of lock. What I've been thinking of is a meter that counts the amount of oxygen that every single occupant in the lock is breathing. So we can say, "His O_2 dose is sufficient, he can go out," or he has to breathe a little bit longer. So we might end up with a certain dose relation between working time, depth, and a certain oxygen dose. And every worker knows of himself how much oxygen he needs for a certain amount of work at a certain depth: Individual decompression...

Hamilton: We are going to talk about oxygen tomorrow. First the idea of individual decompression is a good one but we don't yet really know how to do it. We know what the characteristics are but the people don't match them. You are supposed to get decompression sickness if you are obese. Well sometimes people do and sometimes they get decompression sickness when they are not obese, and vice versa. We don't yet have enough information to do individualized decompression. But there are environmental factors such as the work level that we do know. Those things are very important.

Sterk: But Bill, there is another thing, that is, when you are working with a limited crew, you know who is susceptible or not, and that's what the point is.

Hamilton: That's right.

Faesecke: Twenty men are here working under pressure and every one of them has his individual susceptibility. As long as we are looking on data like 20,000 dives and 20 cases we will never go down into the individual problems, but on a job like this, when we are together for over 24 months—and on this site everybody knows everyone—and among us doctors, we know who the guy is that will come up with the bends; and he knows it. There is a certain predictability.

Hamilton: You stated, it would be nice to measure the oxygen dose. And then you would know from that whether they had enough decompression. That is true, but liters of oxygen consumed and oxygen dose and decompression effectiveness of oxygen are not all equal. But there is a relationship. None of us can be sure about this, but in my opinion one can get essentially (but not exactly) the same decompression at 3 meters of seawater, 0.3 bars pressure, or at 1 bar, a higher pressure, as long as one is on 100% oxygen, and provided one stages down to the lower pressure (rather than skipping stops to jump there). Thus the amount of oxygen (in liters) one breathes is really not the issue, not necessarily equal to the decompression effectiveness. What matters is the time of exposure.

Faesecke: Well, time is dose.

Hamilton: True, because oxygen can be breathed at different pressures. You get a different dose of oxygen. Now if you figure minutes on oxygen, that matters in decompression, you can do that with your oxygen dose.

Faesecke: Liters of oxygen.

Hamilton: No, that is what I am addressing. Liters of oxygen doesn't do as a measure of decompression, because if you are breathing it at 1 bar versus breathing at 0.3 bar, you are breathing 3 times as much oxygen in the first case but you are not getting 3 times better decompression. But to get to the lower pressure, so you can breathe the oxygen at the lower pressure, you have to stage properly. If you jump there, you are going to have bubble formation. Oxygen really works; it really does improve decompression.

Dr. Ichiro Nashimoto: In Japan nowadays, from a viewpoint of cost effectiveness, at pressures up to 2 bar they use manpower; deeper it may pay to use automated machines.

Sterk: Yes. I will talk about that tomorrow.

Le Péchon: I would like to make a remark on oxygen dose and decompression. There are 2 different parameters during decompression. One is what your lung sees; oxygen replacing inert gas directs the extraction of nitrogen or whatever gas. This is one parameter, and this can be controlled by the partial pressure of the inert gas which makes up the hydrostatic pressure that triggers decompression sickness. So you can try to keep the hydrostatic pressure as high as possible as long as possible and manage the lung to see as little nitrogen as possible. Which means you should stay as deep as possible, as long as possible, provided it is acceptable in terms of oxygen toxicity. That is the other parameter.

Sterk: Again, for the lungs.

Le Péchon: Yes, for the lungs, and for the general dose that you will accumulate.

Faesecke: Wouter, did you find changes in lung function?

Sterk: I found complaints. I did not find spirometric changes, that's something different. Therefore I don't believe quite the Lambertsen data on a 2 percent decrease of vital capacity after 600 units [Lambertsen said 615 units would cause a 4% decrement in vital capacity. Ed.]. But there are other changes in dynamic flows. Well, Dr. Tetzlaff knows best, and perhaps he will talk about it tomorrow.

Le Péchon: Another point: You've presented the importance of the dimensions of the locks. And you must be aware that there is a project of European "Norms" which some of us have discussed for a long time. And this is also part of the decompression problem, because if you don't have room enough to stay there for 2 hours properly seated, you will be exposed to more risk of decompression sickness. So it relates to the environment of the chamber and the "comfort" situation. So the project of the European Norm, which is at revision number 15 and which now includes the rules for using oxygen safely is ready for transmission [to the EC] and probably within 10 years will be in our operations.

Faesecke: We may be unmanned by then.

Unidentified Speaker: One question: The European Market is one legislation for the whole European community. If I look at the legislation of France and Germany and Holland, there are big differences between them. Will my colleague think that there will be one legislation covering the compressed gas work or not?

Sterk: Well, will there be a Euro?

Le Péchon: There are some ways to answer that question. You should add that the British have issued in September last year a new regulation for compressed gas work saying that oxygen should be used but they have not produced any tables. And they have still the Blackpool tables in the regulation. They have issued, or they have just issued a new diving regulation. Which is completely independent. When it comes to an European discussion, we French shall never accept that those regulations will not be under the same cover. So that is the first step. If there is the word "diving" in the regulation, it is finished. We will not accept that. It must be "exposure to pressure." So we are not close to putting that together.

Faesecke: I would suggest a tactical solution to our problems with Europe: The European community accepts the Dutch candidate for the Central Bank and in return we all accept the French tables.

VIII.
NITROGEN: A REVIEW, WITH SPECIAL EMPHASIS ON PERFORMANCE

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To focus on the role of nitrogen narcosis in tunneling and caisson work we draw a lot of our knowledge from diving, but there are some differences. Nitrogen is ubiquitous. That is to say, we cannot get rid of it. It is everywhere, there is nothing we can do about it. The main problem with nitrogen in diving is that it causes narcosis. This is the overwhelming reason why alternative gases are used in diving. In compressed air work it is not quite so much of a problem except when pressures get quite high. A close second is that nitrogen is a terrible gas to get rid of when decompressing. Another reason for alternative gases—but not a special problem of nitrogen—is to be able to control the oxygen level. As far as narcosis is concerned, when it becomes a problem we can deal with it (by avoiding it), but it is something we do have to be concerned about. And nitrogen is dense to breathe at higher pressures, which makes it harder to do heavy work.

For reference, a number of pressures are given here in metres of seawater; ten metres of seawater (msw) is equal to one bar, and both msw and bars are gauge pressure.

Nitrogen narcosis

Nature of narcosis in diving and compressed air work

I once asked a commercial diver to tell me his perspective on nitrogen narcosis (Hamilton, 1985). He said, "Nitrogen narcosis is like the sand beside the road. It doesn't bother us because we don't drive off the pavement. In commercial diving we don't expose ourselves to a degree of narcosis that would make it a problem." So in that application it is a non-issue. It has to be dealt with, but as far as the individual commercial diver having to put up with or tolerate narcosis, it is not necessary. In the U.S. it is legal to dive with air to 220 feet of seawater (fsw), which is 63 or 64 msw, and that definitely is in the zone of narcosis. But if there is any serious work to be done that requires thinking then heliox would be used in that range. So it is an optional problem.

We heard a bit yesterday about the concept of **Martini's Law**. This is a facetious "law," but it has some value as a rule of thumb. A "Martini" is a drink normally made with gin and dry vermouth (but you may not get that when you order a Martini in Europe where a "martini" may be straight dry (white) vermouth, so we are talking about a "Gin Martini"). It might be a good idea to define Martini's Law, to describe what is meant here. This rule says that for each 15 metres of seawater depth (50 fsw) when breathing air one can expect roughly the same narcotic effect as 50 milliliters of ethanol (the amount in a gin Martini).

Although the martini rule has some use, the nature of nitrogen narcosis is not quite the same narcosis as that from ethanol. The effect on performance is about the same, but the mechanism is totally different internally. Nitrogen narcosis is, however, very similar to gaseous anesthesia. If you used halothane or some other gaseous anesthetic, then the effect is believed to be by the same mechanism. So we are really dealing here with a gaseous anesthetic; it is just in a very low dose. As with ethanol, the effect of a given amount of narcosis with nitrogen is highly affected by the individual's specific susceptibility. Some feel it varies from day to day, but in my opinion, not much. However, if you are dragging, if you have a hangover or if you are tired, you might well be more susceptible to narcosis that day. There is great variation in susceptibility between individuals.

I remember one experienced diver doing his first 70-msw dive on trimix (a mix that contains some nitrogen but is rich in helium so that it causes less narcosis than air), which was just being introduced at that time for recreational diving. He said, "I don't like it; I don't have to work hard enough to stay alert." He missed the familiar effort he had to make to keep his mental capabilities when diving with air. This particular diver had a reputation of being a deep air diver. He admitted that using helium was is like switching from black and white to color. Getting rid of the narcosis is a tremendous benefit to brain function.

Narcosis affects the higher centers of the brain. One can still drive a car after 4 Martinis. This is not recommended, especially in Norway, but it can be done. We've all done it, and we know we can do motor skills with minimal decrement, even with a significant amount of narcosis. But if a person has to solve a problem that takes logical reasoning, he or she may be out of luck. Or a situation that involves several problems at once, the need for "multi-tasking." The point is, the kind of thinking a diver may need to do, that may be needed to save a life or prevent getting into a life threatening situation, requires higher brain function, and this is the first to go under narcosis. That is where the impairment is.

Here we make the broad assumption that compressed air workers do not operate in the life threatening environment that a diver does. In the case of this particular tunnel under the Elbe we are actually dealing with divers, so this is a different situation. Someone working in the dry may need higher functions to do the job; it may be a job that requires thinking. But if it is just digging, it most likely does not. So there is a major difference between diving and compressed air work, that the tunnel or caisson worker may not be thrust into a life threatening situation as a result of narcosis. Workers in both sites, diving and tunnel work, may or may not have to do work that requires higher brain centers as part of the job.

The equivalent narcotic depth and the role of oxygen

Technical trimix divers have a calculation they call the "equivalent narcotic depth," or "END." Basically they calculate the partial pressure of nitrogen in the same way that they would do for decompression, counting the nitrogen and ignoring the oxygen. That may work for decompression, but for narcosis one needs to look at the properties of the gases.

Oxygen's properties say that it should be a little more narcotic than nitrogen. However we actually do not know how much oxygen is present in the part of the brain where the narcosis takes place (wherever that is). But we advise divers to consider the oxygen when calculating a predicted narcotic effect.

Avoiding narcosis

What do we do to avoid narcosis? Here we of course take the same approach as the commercial diver just mentioned, we use a gas that does not cause narcosis, helium. Helium keeps us on the pavement. Helium is not narcotic at any pressure. One does not need to replace all the nitrogen with helium, just enough to take the edge off the narcosis. As mentioned above, it is a good idea in calculating the equivalent narcotic depth to add the nitrogen and oxygen partial pressures and compare the sum with the narcosis caused by the same partial pressure of air. This is likely to be true even though the mixture in use might be richer in oxygen than air. This point is moderately controversial. There is precious little data bearing on this, but all the data we know about from people who have tried to look at oxygen narcosis have said that it exists. It is just not very strong, and is probably not consistent.

While diving in bentonite the divers' risks are a little higher than they are in nice clear Bahamian waters, but still the divers are not far from rescue. Somewhere in this range between 40 and 70 metres sea water pressure or 5 to 8 bars absolute one wants to pick a narcosis level that matches the kind of work that needs to be done. What this means is that one may not need to switch to helium mixtures at 30 msw. I think you can probably go well beyond that. The cost here in the normal dry tunnel/caisson operation is not so much for the cost of the gas, but rather the cost of having to wear a mask. This has been shown to be manageable, however (Takashima et al, 1996). Where we are dealing with divers, as in this job, that is not much of an issue since they have to wear masks anyway.

Adaptation or acclimation to narcosis

Another question that has come up over the years about narcosis deals with "adaptation" or "acclimation" to narcosis. "Adaptation" is not really the right word. That sort of implies an evolutionary adaptation. "Acclimation" or "accommodation" are better words. This is the sort of thing that enables a person to get used to an environmental situation, whether it is noise or bright light or temperature or something like that, and to be able to tolerate it by coping with it.

This question has come up regarding divers working every day, and more recently for habitat divers, people living in saturation in a nitrogen mixture. In the latter case we began with the assumption that we could subtract the saturation depth to estimate the narcotic effect during an excursion to a deeper depth or higher pressure. In other words, the assumption was that people get completely adapted to the saturation depth and no longer have narcosis. It turns out that that is a bit optimistic. It is more realistic to say, for someone who is **living** in elevated nitrogen levels, not just being exposed daily, that one can subtract about **half** the nitrogen pressure to estimate the resulting narcotic level (Brauer, 1985). Most people who do this very much learn their own limits. It is very different with different individuals. People learn their own individual limits.

Daily exposure does in fact provide some tolerance. If a person is exposed to narcosis daily he or she will be better able to cope with what comes along. The point is that this is an accommodation to the environment rather than a pharmacological adaptation. The body is affected in exactly the same way, it is just that the brain has learned to deal with it better. This is worth knowing; no matter how much exposure one has, one is not really adapted, but just learns to cope.

But acclimatization to nitrogen narcosis is an important factor; it works, so we can use it.

Role of helium in decompression

For short-duration diving we do not use helium in the mix to improve decompression; helium-rich mixtures actually require longer decompressions. However, if the exposure is long enough, as it is in the caisson environment where you have 6 or 8 hours of exposure to pressure, the decompression following that will very likely be easier with a mixture rich in helium.

I thought at first that this was due only to the algorithm, to the way the calculations work. But in fact experience bears out that this seems to be what happens. Helium is taken up so rapidly by the body that for a short exposure it creates an additional decompression requirement over and above that of an equivalent nitrogen-based mix or air. So, except for long exposures (in diving terms), we do not use helium to reduce decompression. But to appreciate the difference between helium and nitrogen, in total saturation to ascend 30 msw when saturated with nitrogen takes 3 days, and with helium it takes 1 day. In other words, it is 3 times as long for decompression with nitrogen.

But the key to improving decompression is effective use of oxygen more than it is helium.

It would be nice if we could reach some sort of consensus on where we should go with nitrogen. We see people switching to helium mixes everywhere from 30 msw to 70 msw. What are we going to do about this?

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DISCUSSION AFTER DR. HAMILTON'S REVIEW OF NITROGEN

Dr. Wouter Sterk: I was ready to jump in, and as chairman I can. I don't completely agree with you, and you should not be surprised about that. When you talk about tunneling, you mentioned shifts of 6 to 8 hours, well that is not the case, that is for caisson work. In tunneling, as is done here, it has been clearly explained that the maximum time under pressure is somewhere around 3 to 4 hours. And it turns out, and I will talk about this this afternoon, that when you use a little bit of helium in your mixture of nitrogen and oxygen it gives a tremendous decrease in decompression time if you, well, switch your mixtures on your way up in an intelligent way. So that can be a big advantage.

Dr. Hamilton: You can manipulate mixes, but you cannot do anything with air except add oxygen. I was indeed lumping them all together. But your point is well taken, in the type of intervention job we have here it is a different situation. In the intervention job you may have a need for more brain function. But with regard to helium, if you are in helium long enough to pick up a load of it, and if you have the advantage of being able to switch away from helium during decompression, you might get some considerable advantages in decompression. If you stay with that helium mix all the way it is going to take a lot more time.

Sterk: Yes, I agree, but one just puts in a little bit of helium and not the total amount. For heliox, you are quite right. There is no doubt about it

Hamilton: Commercial divers don't use trimix very much.

Sterk: Yes they do.

Mr. Jean-Claude Le Péchon: Yes, it depends on the company

Hamilton: There are some that do, and some that have in the past, but basically the traditional commercial diving pattern, certainly for the U.S. commercial divers, is to use a mix of 90% helium, 10% oxygen, or something like that. There is no nitrogen in the mix.

Sterk: Not in Europe. There are several diving companies, at least in my country.

Hamilton: They are becoming enlightened.

Sterk: Yes. We started doing it in the early 1980s.

Le Péchon: We did trimix dives in the early 1970s, and we never used in my company heliox, never, except for saturation. And it is very evident that trimix is much better than heliox for various reasons which we knew at that time. That is just been discovered now again.

Hamilton: That is exactly right. Note the last point, it has been rediscovered. You say it is changing and I think we're becoming enlightened. Not we, this little group has known about this for a long time, but now it might be that commercial practice is becoming enlightened.

Sterk: Then another thing, when you are talking about caisson work you talk about shifts of 6 to 8 hours and you want to go to depths between 50 and 70 msw, 5 to 7 bar, air gives you a tremendous amount of decompression time, so why should you do that, spend all that time in the chamber. You can say oxygen is the option, but you can only use a limited amount of oxygen. So I think it is very unwise, and particularly in my country we don't like to go in caisson work deeper than 35 msw, better 30 msw, on air.

Hamilton: O.K., so you want to use heliox,

Sterk: Trimix!

Hamilton: O.K., trimix, or a helium mixture.

Sterk: Yes!

Hamilton: And the reason being for decompression?

Sterk: The reason being twofold, nowadays we are tending to, also in caisson work, to do it by machinery and then you need highly technical skills for maintenance. So it is not just the digging that is old fashioned, we have passed that. People have to go in for a relatively short time to fix a highly technical problem, and they are skilled people, they must be able to think.

Hamilton: You need to see it in color and not black and white.

Sterk: Right.

Hamilton: When you are doing that kind of work you need the helium to reduce narcosis. What I've said is that you have to look at the kind of work being done, and you have to look at whether it is a life-threatening situation, or a project-threatening situation. If you do something that causes the project to stop you will catch the attention of the client and the taxpayers and everyone else.

Le Péchon: In the operation I've been involved in the problem of nitrogen shows up at not more than 3.3 bar in tunneling operations. The reports we have had from the people is that from 2.5 bar they really experience thinking problems during the exposure. So there is an effect that has been described. Although they were trained they found problems in thinking and in working together; a diver is working alone. When a group is working, narcosis makes a big difference, because they start laughing together. And they have multi-tasking to do, because there are 2 persons and they have to take care of what they are doing and what the other one is doing. This is a multi-task situation; group working is also affected by narcosis. They all report that they have some funny thinking; and they don't work as they usually do beyond 2.5 bar.

There are two different cases. One is heavy work, such as changing tools; then the problem of narcosis is secondary, the main problem is gas density, which makes hard work more difficult. You may have to solve the problem of gas density by reducing the density by putting a certain amount of helium into a trimix. This is one way of dealing with heavy work. Tunneling operations are sometimes heavy work because you need to move heavy tools.

And then there are the other kind of people, technicians doing highly technology repairs. The breathing resistance is not the problem, the problem is narcosis, and the solution is the same. So helium can be used for 2 things, breathing resistance for heavy work and narcosis for high technology, as you described it.

So when should it be changed? Probably due to the special conditions of the work, working in a group, all these problems of the environment are where you can fall down, and where you need to—eventually—move up and down. And moving up and down at 50 msw like this is heavy work under pressure. So even for field work you need to move it. So adding some helium in the mixture, probably in the range of 4 bar, is what I recommend.

Sterk: Absolute or gauge pressure?

Le Péchon: Gauge pressure, yes, operational data. It will be in the range of 4 bar. But the problem is that you cannot fill the chamber with a mix. So people will be working on masks. This is an extra burden for them, training to fix the mask, breathing in a mask, all those problems, if you could do without a mask you would be happier. So putting a mask on people at work for the full duration, having a hose to follow the guy, is another burden. So before making the decision, you have to find out exactly what you want to do. It might be better for a short intervention at 4.2 bar not to go on mask and go on air. It depends on what you want to do. So I don't think we should say that it is a fixed value, we should use this and that.

Hamilton: Note that statement: "We can not set a specific limit that applies to all situations." The cost of wearing a mask is important. However, if you are going under water or under bentonite solution then you have to have a mask, so it is not an issue there. But it may be a factor that needs to be considered.

Le Péchon: The other advantage of using a mix on a mask is that you can adjust the oxygen. And in the range of 4 bar gauge you can use, as you did, 25% oxygen; this reduces the decompression time because you have less inert gas. So as soon as you start accepting masks, you can even use nitrox very well in the range of 2 bars. A problem is the mask and the contamination of the atmosphere with this oxidizing gas. So there are many solutions, but don't cast rigid rules just yet.

Dr. Jan Risberg: You said that the limit for nitrogen narcosis was 50 msw, previously we heard it was 10 msw. As far as I read the literature, no one sees nitrogen narcosis shallower then 20 msw. Scientifically it starts between 20 and 30 msw.

Hamilton: That's where you can begin to pick it up with very sensitive detectors. It is hard to do but I know one diver-scientist who was in the Hydro-Lab at 42 fsw (12 msw), and he said his lips where numb. That's one of the first symptoms. In fact, that is what the word narcosis means, it means numbing.

Risberg: I believe you should be careful with that kind of statement, because divers say a lot of things. I don't disagree with the observation, only the fact that it is very hard to give sound advise based on that kind of experience.

Hamilton: We don't set the limit based on the fact that we know a person had numb lips at 12 msw. I think we based the limit on overall experience. I think what Jean-Claude said is about right, about 4 bars, 4 bars gauge. This is where you start thinking about it. And then you factor in the work that needs to be done, the safety, and the cost of wearing a mask.

Risberg: In my opinion one has to draw the lower limit between some 20 and 30 msw, depending on what kind of criteria you would like to put on nitrogen narcosis.

Secondly, I disagree somewhat when you say that you experience accommodation. I think you used that word and not adaptation. Because if you examine this with neuropsychological tests, you observe normalization, normalization on the tests. Would you call that adaptation?

Hamilton: If I understand you correctly, you have to control normalization by reaching a plateau before you change the mixture, before you change from your control to your experimental mixture. You are quite right that if you take the same test for 3 or 4 days, your scores are going to improve, in almost any test you take that will be the case. Is that what you are saying?

Risberg: This has been controlled with the surface level testing compared to pressure testing. I believe the limit is 4 or 5 days of diving when you observe the adaptation process, when you score better compared to the surface controls. When you do this on neuropsychological tests it can really be accommodation, because you cannot control your degree of trembling or your arithmetic score or whatever. So I would consider that what happens if you are under air saturation for a number of days or do repetitive dives, you get real adaptation, what you call pharmacological adaptation, in my opinion.

Hamilton: Would you summarize that, please? I'm not sure that I've followed what your point is.

Risberg: If I interpreted you correctly you would after some days of diving be able to cope with it, which I surely agree. That could be just due to the fact that you know your environment, you know how to deal with the feeling of nitrogen narcosis. Nevertheless, the same objective effects on your body would be there. That is your coordination, your way of solving arithmetic problems, your memory and things like that.

Hamilton: If we had a real good way to measure the things that are not improved by your learning to cope, that would be the case. The reference by Brauer (1985) is my reason for saying that you don't have a pharmacological adaptation. Your body still is affected in the same manner, but you can deal with it better.

Risberg: My opinion is that the way we can measure nitrogen narcosis objectively, with a battery of psychological tests, demonstrates improvement if we dive for many days. And that is an improvement which is not due to your way of learning the tests, but due to a real pharmacological adaptation, in a way. I disagree with your statement about what I am saying.

Hamilton: You think there is a pharmacological adaptation.

Risberg: Yes.

IX. OXYGEN: TACTICS FOR TOLERATING EXPOSURE

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Introduction

We have to have it. Oxygen is essential in the sophisticated compressed air operation, and we have to learn to tolerate it. We have some new twists on the classical tolerance methods, and an unrelated and relatively new incentive that has led to the development of new approaches. Present-day oxygen tolerance technique has been slightly enriched by a new move into deeper water by recreational divers. These divers have created a need for better methods, and have worked out some empirical solutions. Oxygen is used in deep diving mixes, and as we are discussing here, it will be used in more tunnel work and caisson work where there is control over the breathing mix.

The development of the current techniques for managing oxygen exposure has some interesting history; this presentation touches on some of the high points of that history.

In terms of application, we are concerned about the application of hyperoxia to compressed air work. Oxygen is used for both optimized decompressions, and for treatment of decompression disorders. It is now well established that it is essential to use oxygen for proper treatment, and it is also important to know that these treatments can in some cases be limited by oxygen exposure.

Unfortunately, one cannot increase the oxygen in the caisson, tunnel, or lock atmosphere without a substantial fire risk. In fact, just air at pressures of 5 bar gauge pressure, for example, supports combustion vigorously. This is not news to the compressed air community. This means, of course, that only when breathing mixtures are given by mask that these techniques can be implemented. However, as the need for deeper tunnels and caissons increases, these methods become more and more relevant.

Physiologically, as this group knows, there are two main components or manifestations of oxygen toxicity. The first is the effect on the central nervous system of short term exposures at relatively high levels, lumped here under "CNS toxicity." Effects of longer exposures to lower levels on the lung and other parts of the body have been known traditionally as "pulmonary" or "lung" oxygen toxicity, but in recent years this category has been expanded to include other parts of the body and the peripheral nervous system, and has been designated, for want of a better term, as "whole-body" toxicity (Hamilton, 1989).

The approaches used for managing both of these toxicities is with exposure limits. Methods for doing this are given below.

Although it is highly relevant to the use of oxygen in compressed air operations, the matter of fire safety is not addressed here specifically.

CNS toxicity

The toxicity of oxygen to the central nervous system is not much of a factor in the normal compressed air work environment. The pressures are not high enough and the oxygen levels are not high enough for this to be a concern. Further, the life-threatening risks to a compressed air worker of CNS oxygen poisoning in a dry environment are substantially less than to an untethered diver breathing on a mouthpiece.

Consider first the nature of CNS toxicity. Although there may be several lesser indicators of excessive exposure for a given individual at a given moment, some such as visual disturbances or twitching may act as indicators; these are usually covered in diver training. The symptom of concern is an epileptic-like convulsion or seizure. This will usually cause a diver breathing on a mouthpiece to spit it out, leading to either a dramatic rescue or a drowning, and even in cases where there is no drowning risk (such as a diver in a hard hat or in a chamber) it can be highly disruptive. And further, we do have treatment as an exposure factor; Dr. Faesecke reports on a diver injured in the treatment chamber due to a seizure.

Individual sensitivity is exacerbated by carbon dioxide and by anything that may cause it to increase, such as exercise, breathing resistance, and even a reduced personal response to CO_2 manifested as reduced ventilation. Immersion increases sensitivity to CNS toxicity, and temperature extremes may do likewise.

Toxic effects appear to be related to an exposure level and a duration of exposure. It might be considered that toxicity is based on an exposure "dose," which is a function of the oxygen partial pressure (PO_2) and the duration of exposure to that pressure. When PO_2 exposure levels are higher a shorter time is needed to reach the point where symptoms develop, and at lower exposure levels the time to a convulsion gets longer and the possibility of its occurrence becomes increasingly less likely.

In broad terms, the exposure levels of concern are those above a PO_2 of about 1.6 atm (or bar), a level that can put a person at risk after an exposure of perhaps an hour; this depends greatly on the individual's sensitivity and the exposure situation.

As mentioned, CNS toxicity is not important in normal compressed air work, but new developments of deeper caisson work using trimixes and other special breathing gas patterns can cause us to take a new look at oxygen management, and to look at some new approaches that have come up for dealing with it.

Pulmonary or "whole-body" toxicity

With long term exposure of the sort that affects the lung, as Dr. Sterk discusses in Chapter V, a lot of other factors come into play; different parts of the body are involved, sometimes even without the lungs being affected. So we have to be concerned about these things.

Consider this other kind of low-level non-pulmonary oxygen toxicity. Walter Sterk has been working for over seven years on this phenomenon, and his work shows quite clearly that it is not just lung toxicity. He has seen such symptoms as paresthesias, nausea, dizziness, headache, and a reduction in aerobic capacity (Sterk, 1986; 1987; Sterk and Schrier, 1985). Groping for a term that extends beyond the lung, I tried calling this syndrome "somatic" oxygen toxicity since it affects many other parts of the body in addition to the lung. This proved to be confusing, so I just call it "whole-body toxicity" (Hamilton, 1989).

Prof. Lambertsen and colleagues at the University of Pennsylvania focused on the lung because it was one of the first things to be affected, and also because he could measure a change in oxygen's effect on the lung using vital capacity. He called it **pulmonary toxicity**, and he and his colleagues developed a quantitative measure for it.

The measure of pulmonary/whole-body toxicity uses dose units. A **unit dose** is equivalent to one minute of exposure to a partial pressure of one atmosphere of oxygen; when the PO_2 is above one atmosphere exposure effects accumulate a little faster, and when below one atmosphere units accumulate a little slower. There's a 0.5 atm PO_2 threshold below which units do not accumulate. The equation for calculating these units is a simple power function, which was a curve fit matched to the data set available at the time; the equation is available in many places (Shilling et al, 1976; Wright, 1972).

The Pennsylvania team called this the Unit Pulmonary Toxicity Dose, UPTD. When they are allowed to accumulate, the total is a Cumulative Pulmonary Toxicity Dose or CPTD. A new practical approach is covered below.

History of oxygen limits

The U.S. Navy's approach to CNS oxygen tolerance

The U.S. Navy in the years before 1970 issued the set of limits shown in Table I, which I believe first appeared in the 1970 US Navy Diving Manual. This chart is for mixed gas divers; another less restrictive one covers divers on pure oxygen rebreathers. The limits on the chart show tolerable exposure durations

Table I. USN Oxygen Limits for mixed gas diving (From US Navy Diving Manuals, 1970 through 1992).

Normal Exposures

Exposure time (min)	Maximum oxygen partial pressure (atmospheres)
30	1.6
40	1.5
50	1.4
60	1.3
80	1.2
120	1.1
240	1.0

Exceptional exposures

30	2.0
40	1.9
60	1.8
80	1.7
100	1.6
120	1.5
180	1.4
240	1.3

at different levels of PO_2. For 1.6 atm the chart allows a 30-minute exposure. This is a reasonable exposure limit, and I would agree with it as being physiologically reasonable and operationally tolerable. But the next limit of 40 minutes at a PO_2 of 1.5 atm is beginning to get rather conservative. To carry on down, a limit of 50 minutes at 1.4 atm is absurdly conservative, and it gets worse from there. If these are plotted on a graph it makes a straight line. Lines this straight are unusual in biological systems. This chart is said to have been developed in response to an accident. The Exceptional Exposure chart has significantly higher risk limits. The manual does not offer much guidance on how much higher the risk is or how to use the higher limits, and they required high level approval to be used. These are the only limits given in the 1963 diving manual.

This approach to the management of CNS toxicity in the U.S. Navy Diving Manual has the character of being engraved in brass. This is partly because there was nothing else out there that attempted to deal with this problem. This chart was widely used and accepted, and was even incorporated into national standards. We were stuck with this little chart for some years until getting some relief from NOAA, covered next.

Recently the Navy has taken a different approach. Instead of a set of exposure levels with time limits, the new approach from the 1993 and subsequent editions of the diving manual allows exposure to levels up to 1.3 atm PO_2 and does not set time limits.

Relevant to this, the Navy formerly required that diver candidates take an oxygen tolerance test. This was an exposure to 100% oxygen at 2.8 atm (60 fsw or 18 msw) for half an hour. This test was useful for screening out candidates who could not tolerate being in a small chamber and breathing by mask, but it had too high a level of both false positive and false negative results and was discontinued.

NOAA's Approach

NOAA limits chart

During the time when the little chart in Table I was in effect, NOAA, the National Oceanic and Atmospheric Administration of the U.S. Department of Commerce, began developing a diving technique known as "habitat diving." Aquanauts live in a seafloor habitat, and they soon become saturated, equilibrated with the inert gas pressure at the level of the habitat (Miller et al, 1976). Most of the work done by habitat aquanauts is done during depth or pressure "excursions," during which the aquanauts may descend (usually) or sometimes ascend to a worksite. Over a certain part of the pressure range the excursions can be independent of time, such that the duration of the excursion may be unlimited. Beyond this range, if an aquanaut wants to stay longer it may require the use of decompression stops to return to the habitat.

The use of excursions from saturation creates a new need for oxygen tolerance methods. In diving from the surface with air one cannot easily get oxygen toxicity because decompression requirements keep the exposures too short. One might possibly encounter CNS toxicity, but whole-body toxicity in surface-oriented air diving is not likely. However, a diver in a seafloor habitat saturated at 35 msw (115 fsw; 4.5 atm abs) for example can excurse with air as the breathing gas to 60 msw (200 fsw, 7 atm abs, PO_2 >1.4 atm) and stay 4 h, and can do this every day. Thus we can encounter a significant oxygen exposure on an excursion that could not be made at all from the surface. Likewise, somewhat deeper excursions could put a diver into a range where CNS toxicity could be a threat. In both cases the exposure would be well above the values in the older USN chart. These exposures became possible only when we started making excursions from habitats. From the beginning of NOAA's involvement with habitat diving the prevailing USN oxygen limits caused confusion at the least, and their impact on NOAA operations was significant (NOAA, 1979). So NOAA had to have an oxygen tolerance algorithm for saturation-excursion diving.

NOAA began by asking Dr. C.J. Lambertsen to devise a limits chart that was physiologically valid and operationally useful. Dr. Lambertsen and colleagues, in particular Dr. Russ Peterson, put together the chart that ended up in the 1991 edition of the NOAA Diving Manual (Table II). It was reviewed by other experts. The chart was not calculated by a specific mathematical algorithm, but rather was done as a composite of the experience of Dr.

Table II. Oxygen Partial Pressure and Exposure Time Limits. (NOAA Diving Manual 1991).

NOAA normal exposure oxygen partial pressure limits		
Oxygen partial pressure (PO_2) in atm	**Maximum duration for a single exposure (min)**	**Daily limit: Maximum total duration for any 24-hour day (min)**
1.6	45	150
1.5	120	180
1.4	150	180
1.3	180	210
1.2	210	240
1.1	240	270
1.0	300	300
0.9	360	360
0.8	450	450
0.7	570	570
0.6	720	720
Exceptional exposure limits (Life saving operations)		
2.0	30	
1.9	45	
1.8	60	
1.7	75	
1.6	120	
1.5	150	
1.4	180	
1.3	240	

Normal exposures are those involved in standard diving operations.
A series of repetitive dives may be accumulated within a single limit.
If single limit is exceeded wait 2 h. If day limit is exceeded wait 12 h.

Lambertsen and his colleagues; that it was derived from the USN chart is apparent. The chart takes into account both CNS and whole-body or pulmonary toxicity, and covers exposure over a full 24-hr day. It allows a little more time for the critical level of 1.6 atm, and considerably more for the lower levels where the Navy chart is unrealistic. This chart is for diving under ideal conditions, without heavy work, dense gas, breathing resistance, or the like.

The recreational divers do an interesting thing with this by interpolating the limits chart. For example, if one is allowed 120 min at 1.5 atm PO_2 and has spent 60 minutes, this is an accumulation of 50% of the limit. Both depth and exposure time can be interpolated (Kenyon and Hamilton, 1989). The divers call this the "oxygen clock." There is no experimental bases for this, but it makes sense physiologically because this seems to be a linear function. And it does seem to work in practice.

The Repex project

Although the 1991 chart improved the situation for the initial NOAA excursions, NOAA had in the meantime sponsored research, designated "Repex," that allowed repetitive excursions and excursions long enough to require decompression stops on return to the habitat. Serendipitously, in order to prepare the excursion tables it was necessary to deal with the matter of oxygen exposure, since the only guidelines available at the time were those in the original USN chart, Table I. So, as part of the Repex repetitive excursion project, an algorithm for dealing with the long exposures to oxygen was developed (Hamilton, Kenyon, et al, 1988; Hamilton, Kenyon, and Peterson, 1988; Hamilton, 1989). This was done entirely by reviewing and analyzing empirical data.

We began by looking at oxygen exposure experience. Dr. Sterk's experiments were an important part of that. It became clear that we should look at tolerance over several days, a **"mission,"** not just one day. We began with the observation that a diver who had not been exposed to oxygen recently (say more than a week) had more tolerance than one who had been subjected to daily exposures. From operation diving we had found that the first day about 850 units appears to be tolerable, and Dr. Sterk's numbers agree with this.

The Repex method uses the same equation for a unit of exposure as developed by Lambertsen and colleagues (Bardin and Lambertsen, 1970; Wright, 1972) and mentioned above, a UPTD unit being essentially an exposure of 1 min at a level of 1 atm PO_2. It was my perception that these UPTD/CPTD units were confusing to many people. And I also felt that they focus only on the lung, which as Dr. Sterk has told us does not tell the whole story. Further, in my opinion the original UPTD/CPTD approach did not have a **well defined limit**; it had not been clear (again, in my opinion) how many of these units are an acceptable dose for specific situations. One of the reasons why that had not been done is because there is really no provision for **recovery** in that equation. That is a single exposure equation.

Using the concept of a "mission" or multi-day exposure and combining exposure data from several sources we put together the exposure plan seen in Figure 1. Repex uses the same units but calls them Oxygen Tolerance Units, OTUs. A listing of the units found to be tolerated in the Repex project is given in Figure 1 (Hamilton, Kenyon, et al, 1988; Hamilton, Kenyon, and Peterson, 1988; Hamilton, 1989). As long as the exposure stays below the line it is acceptable for operational use. This means a worker should be able to tolerate a USN Table 6 treatment with minimal symptoms. CNS exposure was managed in Repex by limiting the excursion time to within the limits of the NOAA oxygen limits chart.

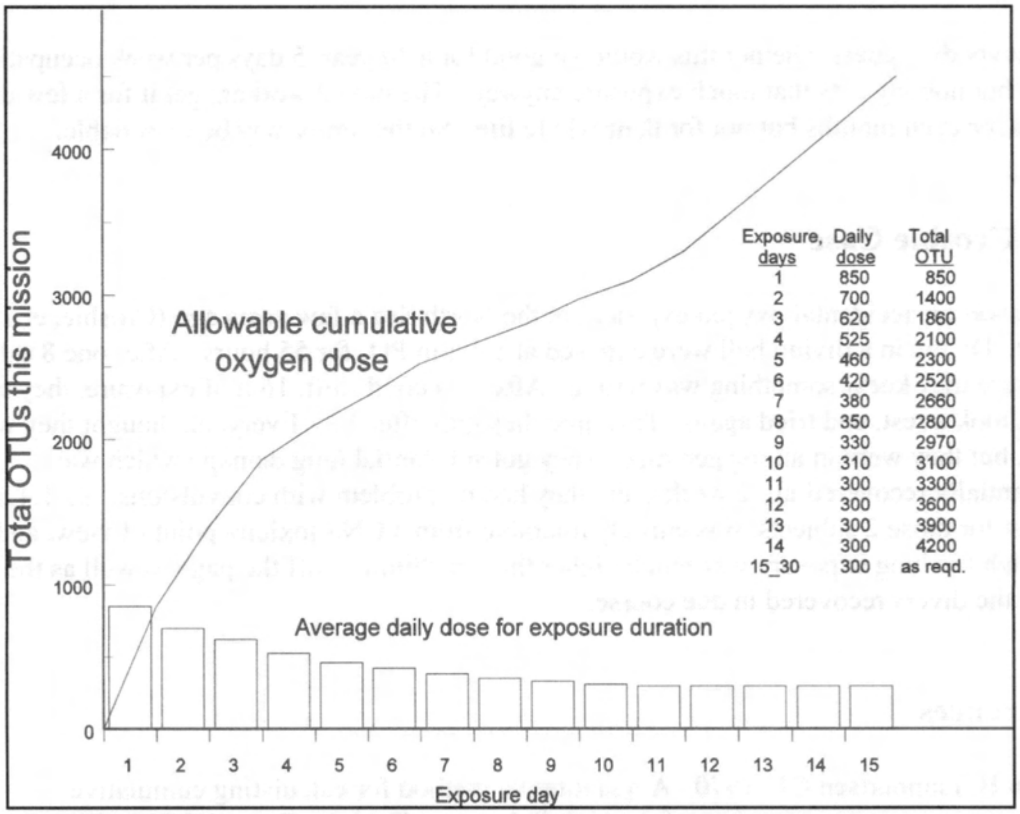

Figure 1. Repex oxygen tolerance limits. Units are OTUs, with each unit calculated the same way as UPTD. In the chart, the exposures that should be tolerated are shown as average daily doses in the second column, and the mission total up to that day in the third column (from Hamilton, 1989).

Note that for a "clean" exposure we are allowed the "hump," the initial exposure at higher levels. The individual daily exposure limits are shown in the chart and by the bars at the bottom. We eventually have to pay it back and get back to a normal daily dose, but in the first few days of an exposure one can tolerate a great deal more. The "hump" is not especially beneficial in long-duration caisson work. It is much more important in diving and possibly the intermittent exposures of tunnel work, and especially in treatment. This chart can be extremely useful in estimating the oxygen exposure cost of a treatment. The daily dose after several days is the basis for multi-day tunnel and caisson work in which workers are exposed every day. Note that one does not need to use the graph, just the little chart.

The daily exposure limit, as others have suggested, rounds out at about 300 OTU per day for a continuous daily exposure, or about 450 units per day for a 5-day week. The 300 units/day can also be regarded as the elusive rate of recovery.

Note that these are "typical" predictive values useful for planning. Some individuals may not tolerate exposures below the line, and others may be able to tolerate a great deal more. The plan presumes the exposures are intermittent. One does not look at the daily exposure but rather the cumulative exposure during a mission. A mission may be several days of an operation or a long treatment or whatever, a series of days of exposure taken together. The little chart on the right shows tolerable daily and total exposures for missions of the durations shown.

It is anybody's guess whether this would be good for a 40 year, 5 days per week occupational limit, but nobody gets that much exposure anyway. The tunnel workers get it for a few days, weeks, or even months but not for their whole life. So the limits may be reasonable.

The Crosbie Case

There was an accidental oxygen exposure in the North Sea a few years ago (Crosbie, et al, 1982). Divers in a diving bell were exposed at 1.4 atm PO_2 for 55 hours. After one 8 to 10 h exposure they knew something was wrong. After a second shift, 16 h of exposure, they quit work, took a rest, and tried again. This time they quit after 1 h. Everyone thought they were in air, but they were in an oxygen mix. They got substantial lung damage which was substantially recovered in 12 weeks, and they had no problem with convulsions. So 1.4 atm, at least for those 2 subjects, was entirely tolerable from a CNS toxicity point of view, and although the lung exposure was much higher that the "limits," off the page as well as the chart, the divers recovered in due course.

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DISCUSSION AFTER DR. HAMILTON ON OXYGEN

Dr. Wouter Sterk: May I add something? It is funny though that during the Eastern Schelde or after the Eastern Schelde experiments on 600 to 800 CPTD per day for 2 weeks that when we saw it was too much I was not allowed to do any further research on that because of the costs.

Dr. RW "Bill" Hamilton: To try to find the right exposure in units?

Sterk: Yes, and then I said, well, let's halve it, lets take 300 CPTD per day. That's what's coming up for the long term; it was a lucky guess.

Hamilton: Several sources give totally different perspectives.

Sterk: Yes, but after that I started to analyze the long exposure air diving tables in which we used a lot of oxygen I then came to the conclusion based on this set of data that about 400 to 450 units on a working week basis, 5 days a week, would be fine for the population.

Mr. Jean-Claude Le Péchon: That's the same!

Sterk: It's the same.

Dr. Jan Risberg: I am really happy to have the possibility to discuss this. Of course I have seen the tables, but I really don't know how they were developed. And I still don't quite understand it. What I wonder is, what is the scientific basis for it? Is this being done with vital capacity measurements? How was it developed? I didn't get that.

Hamilton: Well, Lambertsen originally began to measure oxygen toxicity with vital capacity changes. That was extremely useful but it also had its limitations. Walter talked about that in some detail yesterday.

Walter's experiments(Chapter V)on the Eastern Schelde were the basis for this. And knew from lab work at Tonawanda and Tarrytown that we could do 850 units the first day and come out of it all right, with still enough tolerance to do a treatment (about 600 OTU), but you will begin to get mild symptoms. We don't expect one to go through this without some symptoms. As with any other medical treatment, one may get side effects. But it is still tolerable. You would treat someone who had this degree of exposure. Remember the North Sea case where the divers would be up to the ceiling on the chart. Very, very much more exposure than this. They got sick, but they tolerated it. The British lab did some exposures. I think they did 600 units twice a day or something like that; after about 3 days they got so sick they had to stop the experiment.

Walter was doing 1200 units a day, weren't you?

Sterk: No I was doing 800 units a day. And on the third day I started to get so many complaints from the divers that we stopped the experiment.

Hamilton: But see, the Repex chart says you can do 1860 units over 3 days. You got up to 2400 units and you began to get symptoms.

Sterk: At the end of the week they had gathered 4000 units in 5 days and than we stopped.

Hamilton: That was a serious exposure.

Sterk: Yes.

Hamilton: So there have been a number of exposures that we can compare. Dots here and there on this chart to try to focus on this fuzzy line.

Risberg: Am I right when I say that you have a number of data points, and then you have to do draw the line. You haven't really drawn a straight line through a number of exactly observed points where no pulmonary effects were observed, is that correct?

Hamilton: The initial 850 point is firmly based on data. Some others are based on experience, from the experience Walter did, and a few others, but there were not many data points. Three were not very many subjects, but we are confident that they are relevant because the subjects all behaved about the same way. We know we are dealing with the phenomenon we are studying, we are not dealing with outliers. These are based on data; this is empirical. It is true that some parts of it are smoothed in. But we also have some long term exposures from the SHAD/Nisat done at the Navy Submarine Medical Research Lab where they were looking at month-long exposures to oxygen from a submarine medical point of view (Hamilton, Adams, et al, 1984). So this was put together from data that does not show here (for example, (Hamilton, Kenyon, and Peterson, 1988; Hamilton, 1989). The REPEX report goes into some detail about how we got there.

Sterk: Another thing is that I think, correct me if I am wrong, that the pulmonary limits curve of Lambertsen was based on quite a few data points.

Hamilton: Indeed, they used many points and a mathematical equation that is essentially a curve fit to give you the unit dose as a descriptive unit. Repex is a way that Walter's data and my data can be compared, and Lambertsen's. That's all the unit does; I renamed it "OTU" to make it easier to use.

Risberg: I stick to this because it is very important. I believe when we in the future discuss how much oxygen is tolerable we will constantly come back to Repex; that's why I am working with it. Am I right that the criteria for accepting an oxygen dose is that no there is effect on the spirometry and no subjective symptoms, or is it different, different criteria at different stages of the spirometry?

Hamilton: Let me try to say what this line actually represents with regard to the symptoms. People operating just a little above the line sometimes say they have "chest tightness." In other words, it is hard to separate that from just living under pressure. But the oxygen is probably having an effect. I am calling this an operational limit. It is something I would be willing to go through myself, and something I would be willing to subject a diver or worker to. I mean I consider this a proper occupational exposure. But that does not mean that it is absolutely without effect. I am saying that any effects it has should be tolerable and you can recover from them promptly as soon as you stop the exposure. Nice thing about this is that unless you are trapped in a habitat or in a sunken submarine or something you can deal with this by stopping the exposure and you recover. It may take a while, but you can do it.

Sterk: Just for the record, you said for the oxygen limit we come back constantly to the Repex data. But is this continuous exposure? For the exposure on a working week basis as in tunneling or in caisson work we look at the Eastern Schelde measurements as well ((Sterk, 1986; 1987; Sterk and Schrier, 1985). This is based on analysis of long exposure air diving data. So on a working week basis it's different from continuous exposure.

Hamilton: There are some fine points to this. We assumed that the data from Lambertsen and Clark (which apply here) assumed intermittent exposure. It is difficult to get these levels without being intermittent. Only by living in a habitat with exactly the right PO_2 would you get this on an continuous basis. This whole Repex thing is based on living in a habitat in low oxygen and then going on excursions that provide the oxygen exposure, you might say chunks of oxygen. But it really works. We have something we can really use to estimate the oxygen exposure for tunnel work, to predict it.

Risberg: Bill, could you tell us what the "CNS percentage" is; we meet it all over in the popular press.

Hamilton: O.K., looking at the CNS limits chart, if you spent the total time allowed then you have 100% of your allowable exposure. That would mean if your pressure is 1.5 bars, you have 120 minutes before you reach the limit. If you stay 120 min at 1.5 bars that is 100% or a fraction of 1.0. If you spend only 60 minutes at 1.5 atm PO_2 then you have accumulated only 50% of your total. In that case your CNS percentage is now 50%. It is simply an *estimate* of what fraction of the allowable exposure you have used up at that point.

Risberg: And then you can sum the percentages?

Hamilton: Yes, then you can add them. Again, this was just an arbitrary method, but it seems to work.

Le Péchon: May I make a few comments? The first thing, you spoke about fire in the beginning. I think we have to make very clear that air can not be burned at any pressure.

Hamilton: Air doesn't burn, no.

Le Péchon: This is extremely important in tunneling operations, oxygen doesn't burn either. You often need to do welding or grinding, you have sparks everywhere. The risk of fire is not due to air. It is due to substances which in air at high pressure burn much faster than normally. So this a very important point in safety, to make sure that you do your operation safely.

Hamilton: I could comment more on the flammability. Air at higher pressures, 5-6 bars pressure, supports combustion at a much faster rate. I say tunnel people know this because it is a serious problem at any tunneling operation under compressed air; when you start enriching it with oxygen you get something like what happened in Milan, a fatal fire. But air itself is not innocuous; it gets worse when you go to higher pressures, air doesn't burn, oxygen doesn't burn, but the flammability of everything else goes up.

Le Péchon: Steel burns in pure oxygen.

Hamilton: That's a good point.

Le Péchon: I want to come back to the toxicity. First of all the scale for CNS toxicity, adding up the percentage of the exposure, is really something to be used very carefully, because it is absolutely not linear. When you add a certain number of minutes at 1.6 to a certain number of minutes at 1.2, it is like adding carrots and cabbage. And then you say I have a certain number of vegetables, but it is absolutely meaningless in terms of physiology.

And I think this is very useful for training agencies, for so called technical divers, it makes them exercise. But it is of no value, in my point of view, to add up things that are absolutely different. I accept it if you are adding 1.4 and 1.5. But if you are adding 1.5 and 1 bar it is absolutely meaningless so we should be very careful. It is not even an indication, because the time for convulsion at 1 bar is probably infinite, you will never convulse. So you are adding an percentage of an infinity to something that has a limited value so you should be careful.

Hamilton: True, you are not getting any units at that point. [But I think you have missed the point. You are not adding just minutes, you are adding *portions of a limit*. and those accumulate at very different rates. That takes the non-linearity you mention into account.]

Le Péchon: No, but you have a duration of exposure.

Hamilton: That's the chart that NOAA published.

Le Péchon: So if you use that on U.S. Navy values, it's worse.

Another point is on the pulmonary toxicity. I think this is a very useful means to have a rough evaluation of what you are doing. But when I see values with 3 digits, I am afraid, and even the second one may be meaningless. This is a rough evaluation. In a tunneling operation it is only the decompression that makes a problem. Because the exposure on air in the range of pressure we are thinking about gives a very small number of OTUs, almost negligible during the exposure. It is only decompression [during oxygen breathing] that counts. During decompression we usually expose people 25 minutes on O_2, a 5 minute break, then 25 minutes on O_2. Which reduces the number of OTU more than the 5 minute break. So it is an indication, it is very useful, we have to evaluate them. But we also have to be also very careful not to try to be too precise. It's just a rough indication, but it is extremely useful. But it is not "scientific" and I understand your concern. If you can stay in the range of the curve, probably this curve should be very thick, then it will help you. The rule of stopping oxygen during the exposure reduces very significantly the immediate effect. And in the tables with oxygen there are 2 reasons to stop the masks. The first one is that people are playing cards and they need to count the points from time to time. They also need to exchange information about what they've done, so they need to remove the mask every half an hour just for social reasons. And also wearing a mask for a long duration is not very comfortable. So a break is always welcome. These are operational things. And for the toxicity the break is a big improvement, which is not counted in the calculation, but it is important. So we should remember that we should stick in those values, roughly, for the total exposure. And split it every half an hour, every 15 minutes, from time to time. Then we shall be safe all the time.

Sterk: May I have one more comment? What worried me was that in the new German tables they had set the limits at 300 OTU or CPTD. which I think is not very wise. It is too low for a working week basis. And it is based on 2 things I think. First of all, way back at the Eastern Schelde experience we said 600 is too high, but I can't do further experiments, so let's half it and see what happens, and carry on with continuous exposure. And that's completely different. I think that we should take full advantage of the oxygen for decompression. When you go to higher pressures you need a lot of oxygen to decompress safely. If you are going to longer shifts I think we should consider that. It is possible in other countries, apart from Germany I understand, that you come up to 400 or 500 CPTD or OTU, but with air breaks in between not only for counting the cards or whatever but also to take some fluid, something to drink. That's also very important during decompression.

Hamilton: Let me respond to Jean Claude. I am aware what you say about the lack of real scientific basis for this. Dave Kenyon and I (1989) came up with this business of the fraction, the CNS percentage, and somebody else did also, independently; I have not been able to find out how they got it. On the matter of intermittency, when we had to do some very deep cave dives, nearly 90 meters for 90 minutes, they could only do this by intermittent oxygen breathing, 20 on, 5 off. Now they have done dozens and dozens of these dives. I crossed my fingers at first, but now we are all comfortable with this. Now this is a significant dive in a commercial environment also. They could not do it within the 100% exposure limit. By interrupting—they go on bottom mix during the break—the level is much higher than the NOAA limits would say that you can tolerate.

Le Péchon: May I show you just one thing on a slide? The tables that you've seen on the blue book. There is somewhere written that should be intermittent, but it is not shown in the table. Instead we have introduced the intermittency directly in the presentation of the table. For example, you have 3.5 h
at a pressure of 1.8 bar gauge, and you will have your first stop at 0.9 bar, a 20 minute stop, and you stay on mask until the next stop for 5 minutes, where you have 5 minutes air; so this is incorporated in the table.

Risberg: I agree with you when you talk about whole-body toxicity. The thing I wonder is, isn't it more or less either an academic or semantic expression, because at this time I don't think we have much more than the pulmonary effects to evaluate, do we?

Sterk: No, no.

Hamilton: No, there are a number of things beyond pulmonary.

Risberg: Can we measure them? And use them, I know a number of effects on the eye and the cornea.

Sterk: Well, with careful neurological examination you can measure the numbness in fingertips and toes and you can follow up the recovery, which our neurologist did. I didn't do it myself. I just put it in the hands of specialists and look after them. And it took in some of these cases as long as one month to recover fully. And there are other things. Of course there are subjective symptoms as well. But there are means of measuring those. Extreme fatigue, for instance, was noted, and not just "a little bit tired." There were sportsmen, amateur sportsmen, in this crew, and on the weekend they were not able to run 10 meters behind a ball without becoming exhausted. Well you can measure that with ergometry or whatever. You can use visual analog scales. Of course it is subjective in some way but it is a measure. And for instance in other parts of medicine like pain treatment (I am also involved in that; we are used to living with that). And I agree that we should look for finer methods to detect what's going on. And particularly what causes the numbness: is it vascular, is it neurological, what is it? I don't know. But there should be a means to look at it. I hope you will come up with some answers to that.

Risberg: Well, in my opinion we have 2 areas which we are able to measure concerning oxygen toxicity. One is the brain and seizures, the other is the pulmonary system. Sorry I don't agree with you concerning the fatigue, your loss of physical work capacity. We've seen it in sat diving. We don't know whether it is lack of sunshine or what.

Sterk: It is completely different in nitrox diving. It is not just "a little bit tired." They are exhausted.

Risberg: There is a lack of scientific evidence supporting this in a way that you can measure . We know it on a lot of enzyme systems, we know it on a lot of organs, but we can not today exploit that information, in my opinion.

Sterk: Well I am not quite sure, I think we can if we try hard enough, find the methods. I don't agree that pulmonary symptoms are the only thing we can measure, because in the Eastern Schelde experiments we did not detect any vital capacity decrease as Lambertsen did. If we had had the opportunity to measure expiratory flow rates, et cetera, dynamic things, what is there, total lung capacity, CO diffusion capacity, maybe we would have found something. But we could not, based just on spirometry and x-rays. And not in the blood as a routine analyses. So we should look for other things than only the lungs. That's what I emphasize.

Hamilton: Let me respond to Dr. Risberg. Let's say our objective here is not to provide a scientific analysis, we are looking for something practical that works. We would like to have a better scientific bases for it, but as I said, all we really have to go on is empirical results. Walter's experiments gave us empirical data. I gathered them from a lot of other places, and put them into this curve. This curve is subject to modification as soon as we get more data. It doesn't pretend to be scientifically correct. We don't have that level of information. We would like to have it, but had to go forward because we had to do these exposures.

Dr. Karl Faesecke: At this construction site we've managed to set up a little medical laboratory. I didn't show it to you because I am little bit ashamed about the way it is placed. And of course we will focus on pulmonary symptoms. All that I am waiting for is exposures. Now I have the gear set up and we have not had the exposures until now.

Eight years ago at the Kiel Fjord tunnel, when we went down to 39 meters, we had 2 hours of decompression on oxygen without air breaks. We found no changes whatsoever with a very fine evaluation method. So what we really rely on is the questionnaires again, which is of course rather doubtful, and you'll be running after the tunnel workers all the time to get the data. Because when they come out of the lock they carry on with the work shift for 4 more hours and then they shower and have a meal or what and then drive home. It is very difficult to get a hand on these guys, be it before or after the exposure. Nevertheless, we'll work on that and hopefully we'll get something out.

Now I would like to come to the topics for discussion. Because those 3 questions here are sort of correlated. When someone comes out after 2 hours of decompression and an hour later complains of knee bends or whatever, we are forced to take him down again on oxygen. Of course this is a treatment and I would come back to what Jean Claude said yesterday "Is that lay treatment or not?" And this goes to the third question. Have you ever experienced an oxygen seizure in the chamber during a treatment session, and what are your diving foremen doing in that case? Bill said it is a medical thing, treatment on oxygen in the chamber, of a diver or a compressed air worker. Is that medical treatment? Should it be done by doctors only? Is that lay treatment, can that be done by any diver?

Hamilton: I would like to comment on that and to respond to something Jean Claude said yesterday. In France they call it an emergency when someone has to be treated. But this is a semantic thing, to deal with the structure of the organization. It is not an emergency. It is a necessary step. I am constantly pounding on Peter Bennett (head of DAN, the Diver's Alert Network) not to call decompression sickness in diving an accident. It is an incident. But they have to call it an accident because the insurance system wants it to be an accident. It is not an accident. If you plan your operation, your plans include dealing with decompression sickness. Whether it is a tunnel operation or a diving operation, that is not an emergency, it is not an accident. It is a routine treatment.

It can be done by lay people as long as it works. Certainly at the beginning, you put the people under pressure before the doctor is there. This has been done in the military and commercial diving for much more than half a century, and there is no reason to change that. There have been some improvements; most offshore diving crews have emergency medical technicians out there and they are much better trained to deal with it . But an grizzled old master diver in the navy probably knows a lot more than the young instant doctor that comes in, who is required to be there. So there is nothing wrong with lay treatment. You don't make medical decisions. You don't let laymen make medical decisions but you can certainly have them start an operational practice, a chamber treatment with oxygen. But it very much depends on the administrative environment.

Dr. Ichiro Nashimoto: Concerning Doctor Faesecke´s experience, I also experienced such an oxygen seizure; I don´t quite remember when, about 15 years ago, when the patient who suffered from the bends came to my medical college for hyperbaric treatment. He had undergone some treatment at another place, so my co-workers and I gave him treatment on a Table 6. We administered oxygen at 2.8 bar, and there were two physicians in the chamber. He had no problems with the O_2 mask and the overboard dump system. So the physicians decided to leave the chamber and went into the lock. We kept contact with the patient over the telephone and everything was O.K. Suddenly we could not hear from the patient and realized he could not speak. We were very surprised. I told the physicians to go back in the main chamber. They found the patient all right, only he could not speak. Later I found that the patient had dislocated his jaw due to a cramp.

Sterk: We can learn from that, that hyperbaric oxygen is good for people who speak too much, like myself . . . but I would like to comment also on the suggested topics.

First of all there is the matter of depth of treatment correlated with working depth. In my experience it is not correlated with working depth but the depth of onset of symptoms, if during decompression, or the delay between surfacing and onset of symptoms. So there is no need, if you are diving at let's say 100 msw, to treat somebody who gets bends lets say 4 hours or 5 hours later on saturation at up to 100 meters or more. We can just stick to, for instance, COMEX Table 30 or the U.S. Navy Table 6.

Then about lay treatment . I deal quite a lot with offshore diving. And in offshore diving it is absolutely nonsense to wait for a doctor to arrive, and treatment is an emergency, so they should be treated as soon as possible. The chamber is on the site. We trained experienced divers as paramedics. They can do all kinds of interventions. But they should do it preferably after contacting by radio or phone a medical doctor who has the responsibility. The medical doctor is responsible for the actions of the paramedic as far as medical interventions are concerned. But any diver who has reasonable experience should start recompression treatment as soon as possible. That's the golden rule, and then try to contact a doctor and wait for a couple of hours before he answers because he's out of range or whatever.

The worst experience with oxygen is still the Eastern Schelde experiments, which lasted for 2 weeks. We started the first week with 600 CPTD per day, and the first week went well. On the second week we continued with the 600 and started with the 800, and then I had 12 divers complaining in the second week, and for some it took about a month to recover fully. And we didn't know at that time whether they would recover completely.

Le Péchon: Concerning the semantic problem of whether DCS is an accident. I think that in diving decompression sickness can be induced by an accident, meaning that a diver can blow up. So this is an accident inducing decompression sickness; you can gather the words and say this is a decompression sickness accident. In tunneling operation and caisson work the probability that you won't make the expected decompression is very small because it is fully under control. You cannot blow up. Except if you lose the pressure on the face, which is very improbable but may happen. So decompression sickness in a tunneling operation may not be considered as an accident but as an event associated with the operation. So much for the semantic aspect.

In seizures in recompression cases, when I was in a diving company our doctor has given the policy that recompression should be carried out immediately, as you say, at 1.8 bar gauge. Giving 2.8 bar of oxygen may induce seizures. To prevent seizures it was recommended that the diver be given 5 milligrams of Valium before. So we never had seizures during these opportunities. We never had to face that.

And secondly, then one reason for going only to 1.2 bar during emergency recompression carried out by divers is to prevent the need for this Valium. If the recompression is immediate, it is enough. So the pressure you want to go to depends on the delay between the symptoms and the treatment. If you have an immediate treatment, most of the time 1.2 bar recompression is enough, and you are not in the range of serious risk of seizures. So using the COMEX 1.2 table [Comex 12] is also for prevention of seizures on site. So this is a choice and a decision. So from the tunneling operation the few accidents that we have to deal with in various sites have all been taken care of in the hospital. And to my knowledge they never had seizures. But I don't know if they've given any medication or whatever. So this has been taken care of in the hospital.

A final comment. Among the symptoms you mentioned for long term exposure, there is one which might be questioned. And that we have observed when we do compressed air work every day, decompressing on air. The UPTD is another question. Extreme fatigue, we have it, with those tables. So extreme fatigue can be and it is probably difficult to sort out whether it is an oxygen problem or a decompression problem.

Sterk: We found out that Comroe in 1945, as I said yesterday, experienced symptoms of 100% oxygen breathing at the surface for 24 hours, in some cases longer. They experienced symptoms that were quite the same as decompression illness. So there is always a problem, and looking at my data back then on the long exposures, there are some cases that I considered to be decompression illness. When I reanalyzed them, I am sure, almost sure, that it was just oxygen toxicity. But it was reported some 50 years ago already.

Hamilton: May I finish responding to your question? Table 6 causes about 1 in 1,000 seizures. So you have had one, but one is expected now and then. Yes, you should win the lottery with that luck. The consequences of a seizure are almost entirely mechanical. The individual may have a headache but I have seen experimental subjects return for the experiment the next day after having a seizure. In other words, they don't say, "Never again," because they don't remember anything. If you bite your tongue, okay, that's not so good, you remember that. But we've had injuries from people falling on a hard steel deck. I would not want to do one voluntarily, because anything it does that to your brain is likely to have some effect. But normally it does not have any residual that can be found.

Risberg: The reason I ask for scientific proof is that meanings like this are frequently being used to legitimize certain actions. It's like using certain decompression tables. Certain limits for oxygen and so on, that's okay. But we should say that this is based on the best knowledge we have today, and not on what I would call sound scientific evidence.

In Norway we have at the present time exactly the same problem concerning decompression schedules for sat diving. What we are saying is not that we have found a solution, just that we found a standard. We are making a standard and advise people to follow it. And observe what kind of ill effects occur while using it. We do it based on the best knowledge available but that's definitely not scientific. I think that would be a way of working that can be applied to caisson work as well. In air we don't have enough knowledge. Then to the questions here. The depth of treatment correlated with the working depth. Referring to diving medicine we know that it is probably not. I mean more and more people are moving away from Table 6a and the deep tables. It doesn't seem to be much evidence that this will help in diving decompression illness.

Sterk: Even the U.S. Navy has abandoned the 6a treatment for arterial gas embolism.

Hamilton: Not totally. It is still in the book.

Sterk: It is still in the book but they don't use it any more. There was a presentation on it in Columbia, South Carolina.

Risberg: I would like to finish the lay treatment, which is helpful. It can't be much of a problem if we have classical symptoms with pain in your feet or arms or whatever, you can't do much wrong. The question I wonder is, "If you have neurological symptoms and if you have loss of consciousness, what would then be the consequences?" It doesn't happen frequently that someone gets an embolism or a serious neurological incident. But if you delay treatment for those very few instances the consequence could be serious.

Sterk: I don't agree.

Risberg: O.K. We have observed it. But it is a question of incidence. And as far as I understand, in caisson work and tunnel work neurological DCI is very infrequent, isn't it? So the problem that we'll meet will probably be small and we will be able to cope with it. But if you disagree I would like to know if early treatment of these embolisms is important or not.

Mr. Alexander van Vierbergen: I feel like the winner of a jackpot because you said one case of seizure is special. I have had 5 in 3 months and they happened.

Sterk: On pure oxygen, I hope.

Hamilton: 2.8 atmospheres?

van Vierbergen: Yes, 2.8 atmospheres, and they happened after Dr. Bakker advised us to measure oxygen contents in the mask, and we made the masks fit better and they got seizures. If you call a number of 1 in 1,000, that says more about the mask that the personal fit than about the oxygen content one gets. In the seizures, when I was in control, I never felt any added value of the medical doctor at the spot. Only the paramedics thought I was a sort of *deus ex machina* and they felt more confident because I was there. But I did not do anything except for one case and that was the worst case I experienced. A big guy got totally psychotic after the seizure, and in that case we put him right away on sedatives. But I don't think that a doctor has any added value other than psychological in the treatment situation.

Faesecke: Just to make the round complete, I have to elaborate a bit more on the experience we had here. Aside from the accident itself, or the incident or whatever you call it, this guy broke his nose when he fell off the bunk. We were just 20 minutes into the first O_2 session. This accident brought up all the long forgotten prejudices about oxygen. That's why we spent most of the time talking to the engineers, to the people who are running this construction site: Oxygen is good for them; don't judge from this one accident that we should go away from oxygen; we will continue decompressing on oxygen.

The result of our discussions was, and I consider this accident really stimulating, up until now we had in the German regulations that we may use the COMEX Treatment Table 12 (O_2 at 12 msw) only when we´d been working shallower than 15 meters. That was the experience they first had in Munich. And so we said, let's try it out, even if we are working definitely deeper than 15 meters; up to 30, 32 meters were the deepest exposures. And the treatments we had to perform were all successful on 12 meters O_2 for 2.5 hours. And another consequence of this accident, and you must know that, from the side of the authorities, was that they now require the doctor to be inside the chamber with the patient when the treatment starts and then for the whole duration! We couldn't talk them out of that. So that's the obligation under which we are now. And that reminds me of what Texas Medicare just recently decided, that in HBO_2 treatment the doctor has to be at the chamber, not inside, but at the chamber.

Sterk: To get reimbursement! They may be away from the chamber. That was the reason.

Hamilton: That's right. Because the doctors tended to send a bill for their services while they weren't even there.

Sterk: That's a different situation.

Faesecke: Going back to the follow-up. This man fell from his cot, he broke his nose. He had a bleeding into his orbita. He'll probably never want to go back into compressed air, he is a skilled mechanic, not just one plain guy. I would have no problem giving him permission to go back to compressed air work, including oxygen decompression. But from a psychological point I would not force it on him. I said you can go back, I would allow, but you need not, and I said, "Well, you'd better stay away for a couple of months." But this was really a tremendous thing to happen, there was blood all over in the chamber. And we were in the papers next day with that bloody chamber and that was about the worst thing. It was my third case in 22 years, but this was surely the worst one and it had a lot of consequences. We have to look at those things also. And now everyone is satisfied because the doctor is inside the chamber. He can't do that much, but he is there. And the authorities are satisfied, that's the way things can go.

Sterk: I would prefer though, to lower the maximum pressure and go not to 1.8 but lets say 1.4 or 1.2 bar.

Faesecke: The Swedish tables are 1.5 bar.

Sterk: Okay, as long it is above 1 bar gauge, it is hyperbaric oxygen and it helps.

Le Péchon: Just one word. In the recommendations for the doctors in the French regulations, people going up to 4 bar in compressed air or diving should be screened for epilepsia during the fitness evaluation. And this is done with EEG, with hyperventilation and light simulation. And it does not eliminate many persons, but it has happened that a few of them has been separated. Maybe this is also part of the solution.

Hamilton: Do we know those people are more susceptible to oxygen convulsions?

Le Péchon: No.

Sterk: No, it adds only to the the cost of an examination.

Le Péchon: I shall not discuss that point. I just want to inform you because this is a medical aspect I am not dealing with. But I want to inform you that in our recommendations, our doctors have asked for that. But we have removed the test on oxygen at 18 msw, which as everybody knows is meaningless.

Additional reference:

Hamilton RW, Adams GM, Harvey CA, Knight DR. 1982. SHAD-Nisat: A composite study of shallow saturation diving. Rept 985. Groton, CT: Naval Submarine Medical Research Laboratory.

X.

DO LATEST RESEARCH RESULTS BRING UP A NEED FOR ADDITIONAL HEALTH EXAMS OF DIVERS?

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Introduction

It would take an additional weekend to answer the question accurately. I will focus my presentation on two main important organs of the human body, the lung and the brain. Both may be affected by diving or compressed air work in a two-fold way: Directly in decompression illness and in possible long term health effects from diving exposure.

What is presently performed to assess pulmonary fitness to dive? There is a wide range of recommendations that varies between diving techniques (commercial diving vs. recreational diving vs. military diving) as well as between countries. A worldwide consensus exists concerning the necessity of chest x-ray at the preliminary examination for fitness to dive and of spirometry being performed at regular examinations. Values that should be reached in divers are provided for three lung function variables: The forced vital capacity (FVC), the forced expiratory volume in 1 second (FEV_1), and the FEV_1/FVC ratio. The value of expiratory flow rates at low lung volumes, of maximum oxygen uptake, and of bronchial challenge tests is still under debate. However, a recent tendency of being less restrictive with respect to certain radiological or functional examinations of the lung, at least in Europe and North America, is evident. A chest x-ray for example is now only recommended at the initial diving medical examination and after the age of 40 years, even for professional divers. Thereafter it is recommended to be repeated at certain intervals that differ between countries.

Spirometry should be performed annually. FVC and FEV_1 should exceed 80 % of the predicted normal values and the FEV_1/FVC ratio be greater than 70. Whereas acute respiratory illness, chronic obstructive airway disease (COPD), and chronic lung disease with a reduction of exercise capacity preclude from diving, asthma is no longer considered a contraindication to diving in general, even in professional diving. The worldwide increasing prevalence of allergic asthma and the relatively low incidence of pulmonary barotrauma may account for this leniency. The reason for testing pulmonary function in the medical assessment of fitness to dive is to detect possible airway obstruction and thus prevent divers from being exposed to the risk of suffering pulmonary barotrauma (PBT). Routine spirometry has been carried out in the medical examination of military and commercial divers in the past, although there is no evidence that the incidence of PBT among divers has been reduced since and spirometry has been considered to lack the necessary sensitivity and predictive value to make it useful.

Studies on lung function and PBT in submarine escape tank incidents revealed an association between low values of forced vital capacity and PBT, but this finding lacked an adequate explanation until today and was interpreted as a statistical association rather than a risk index. However, there is some evidence from recent research that airflow obstruction, in particular dysfunction of small airways, may contribute to the risk of suffering from pulmonary barotrauma. In a series of consecutively admitted patients that suffered from decompression illness and in whom pre-injury spirometry was available, we found an apparent decrease of the expiratory flow rates at 50 % and 25 % of FVC (MEF_{50} and MEF_{25}, respectively) when compared to divers that were injured by decompression sickness. Similar findings have previously been reported by Wilmshurst and colleagues (1994). Moreover, in that series, we found a relatively high number of lung cysts (6/15) among patients who had suffered a diving related pulmonary barotrauma which has not been reported previously.

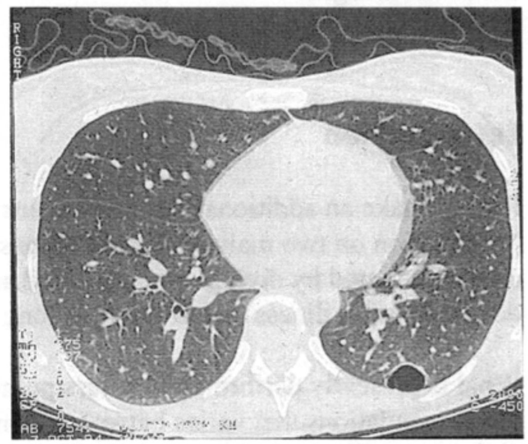

Figure 1. Chest CT of a 25 year old female sport diver (Case 1).

Case studies

Case 1

A 25 year old female sport diver performed a scuba-dive to 28 m in the Red Sea. She suffered from severe power loss and nausea immediately after surfacing and lost consciousness later on. And this is what we found in the lung (Figure 1). You see a lung bleb, 3 centimeter in diameter in the left upper lobe. This is the control CT of the lung we performed one year after the incident. We were astonished that this was not apparent on chest x-ray and we wondered whether this was the cause of the diving accident or pre-existent. You might guess it would change its extent, but it had been stable for one year indicating that it might be pre-existent.

Case 2

This is case of one of our military divers who performed a helmet dive in the Baltic sea. There was a voice change during ascent. After surfacing he lost power and there were some neurological symptoms. What is not shown is computed tomography of the brain. He had a large cerebellar infarction. I think it might be interesting to see what happened to the lung, of course, and CT showed a clear bleb (Figure 2). All the cases that we see here had a diving medical examination before the incident and

Figure 2. Chest CT of a 27 year old male military diver (Case 2).

were found healthy. When you see case reports of arterial gas embolism, you always will find that there has been radiologic examination of the organs that were apparently hit, mostly the central nervous system, but not of the lungs.

Case 3

Another case report of a military diving trainee. He performed a scuba dive with a closed circuit breathing apparatus in the Baltic Sea The breathing gas is pure oxygen. He developed hoarseness 2 hours after surfacing. It was Friday noonwhen he was admitted. The incident was the day beforeand he said, "All is going well." Yesterday he had somehoarseness, maybe some tingling in the throat. And noweverything is going well. Speculating that this was another kind of pulmonary barotrauma, because the symptoms were fitting to mediastinal emphysema, we performed a chest x-ray (Figure 3). CT of the chest was not available at that time but was done on the next Tuesday, the following week. And what we saw in this case was this feature here in the mediastinum. When you look in the book of Edmonds and colleagues *Diving and subaquatic medicine* (1992) you find the description of what may be the 'tram track' sign. Fortunately this diver had been examined in our institute half a year earlier. We could see that there were very slight changes but they are apparent. Even our radiologist did not see this. He did not see the "control" picture.

Figure 3. Chest X-ray of a 22 year old male military diver, showing 'tram track'sign (Case 3).

Figure 4 shows the chest CT performed in the high resolution mode and Figure 5 in spiral

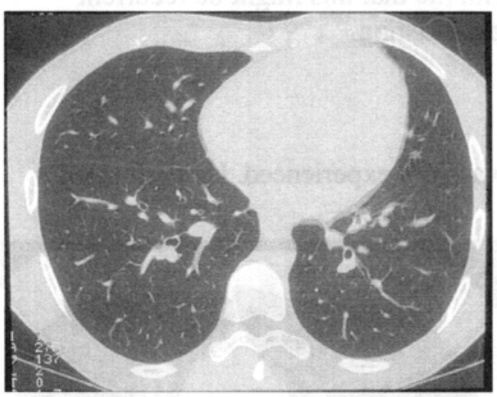

Figure 4. Chest CT, high resolution mode (Case 3).

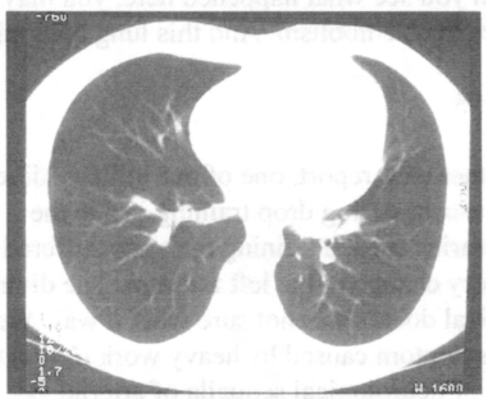

Figure 5. Chest CT, spiral mode (Case 3).

mode. The spiral CT technique enables rotation without a breathing artefact of the patients, so you can locate small areas; I want to focus attention on a lung bleb 3 centimeters in diameter. Mediastinal emphysema had been resolved in the meantime.

Case 4

This is a case report of a female sports diver. She performed a dive in the Mediterranean Sea and suffered from the symptoms of nausea, sensory change, and weakness at the surface. She was treated by pure oxygen several hours and the symptoms completely resolved. She finished her holidays and came to our institute to ask if she's fit to dive further on. Medical history revealed that there was another incident one year ago. She had been treated at that time at the hyperbaric facility of a great Spanish city with a famous soccer club near the Mediterranean Sea. What they did at that time was a computed tomography of the brain. And they did chest x-ray as you see in Figure 6. It is unremarkable. After about 3 months she would be able to dive again.

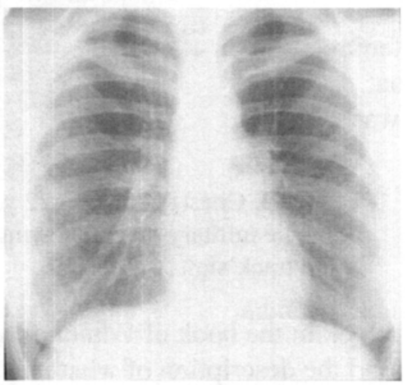

Figure 6. Chest X-ray of a 26 year old female sport diver (Case 4).

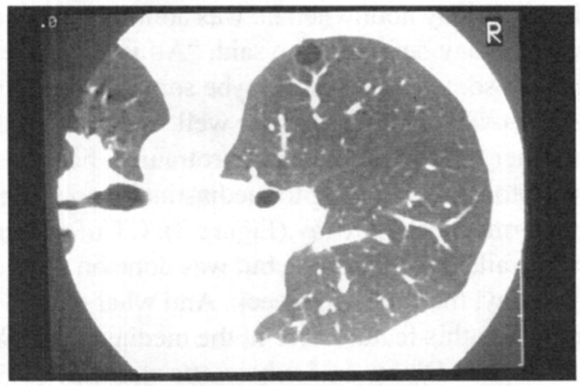

Figure 7. Chest CT of the same diver (Case 4).

What you see in Figure 7, with this patient laying on her back, is another lung bleb. Hence there may be some findings in CT's of the lung that are not apparent in chest x-ray. And when you see what happened here, you may agree with me that this might be recurrent arterial gas embolism. And this lung bleb might be pre-existing.

Case 5

Another case report, one of our military divers. He was very experienced. He performed a free ascent during drop training inside the submarine escape training tank and suffered from sensory change in the left forearm. The diving medical doctor was not sure what it was. Was this symptom caused by heavy work or was this a kind of neurological sequella of arterial gas embolism? The patient was treated with pure oxygen for 3 hours and the symptoms went away. The chest x-ray was unremarkable. This CT was performed one day later (Figure 8). And what you see here is air. Air inside the mediastinum. Hence he had suffered from mediastinal emphysema and from arterial gas embolism.

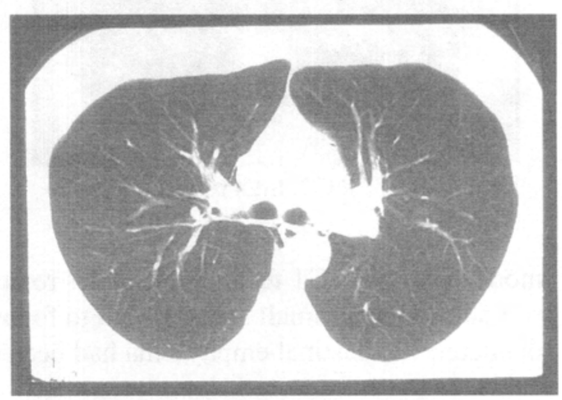

Figure 8. Chest CT of a 27 year old military diver (Case 5).

Case 6

Next I want to present the case of a 29 year old healthy male, an experienced sports diver. When he came to us, one month after his scuba dive, he asked us to assess his further fitness to dive, since there was an incident that happened in his holidays. He reported hoarseness, thickness of the throat, and chest pain after a dive. The symptoms resolved within hours spontaneously. Figure 9 shows the CT of the chest; chest x-ray was unremarkable. I think anyone can see this area of air inside the mediastinum, one month after the injury. We waited 3 months and performed a follow up CT, that showed complete resolution of mediastinal air. This case may illustrate that it may be worthwhile even to perform diagnostics weeks after an incident, when you have the suspicion of pulmonary barotrauma.

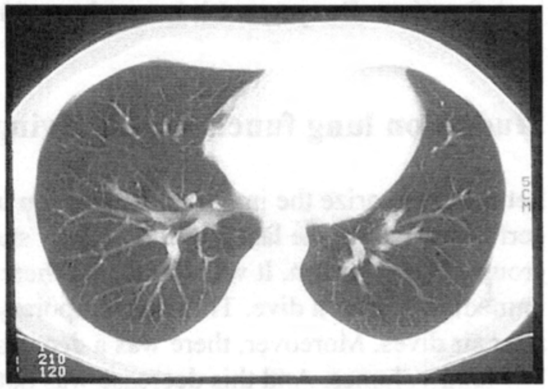

Figure 9. Chest CT of a 29 year old male military diver (Case 6).

Case 7

Another case was a 30 year old male experienced scuba diver. Within 5 minutes after surfacing there was coordination loss, paralysis, and weakness of the right leg. Unfortunately I have no radiologic images of this case. But I have a plot of lung function (Figure 10). He was a military diver, so we had a lung function before and after the diving accident. I want to focus the attention on this. It shows FVC, forced vital capacity, FEV_1, forced expiratory volume in one second, before and after the accident. These two measurements are commonly performed and evaluated for t

he assessment of fitness to dive. It also shows the mid-expiratory flow at 25% of vital capacity (MEF_{25}), characterizing the small airways function. These are percentages of predicted. It was obviously decreased.

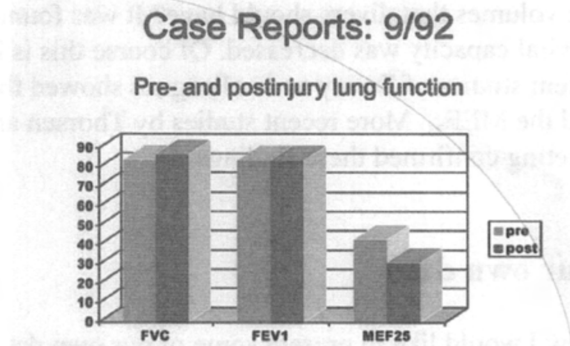

Figure 10. Lung function of a 30 year old military diver in percentage of predicted (Case 7).

Case 8

Another case report of a this 21 year old submarine escape trainee performed a risky dive with an increased risk of suffering from arterial gas embolism, and he did. Figure 11 shows his lung function. Pre dive and post dive and again you see

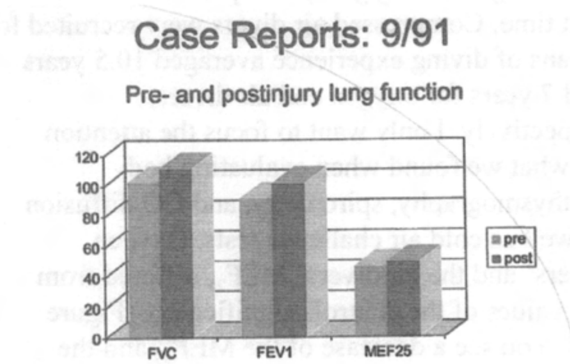

Figure 11. Lung function of a 21 year old submarine escape trainee in percentage of predicted (Case 8).

the decreased MEF_{25}. Interestingly, you see here only 40% of what should be predicted. Maybe there is a pre injury 40% and a post injury 42%, it is within the normal variation of lung function. But you see it is not above 80% and that is what is important.

Studies on lung function and diving

Let me summarize the important studies on lung function and diving that have been performed within the last 20 years. Many studies were performed by the Norwegian working group of Dr. Thorsen. It was found that there was a decrease of pulmonary diffusion capacity immediately after a dive. This was temporary and was found after saturation dives as well as after air dives. Moreover, there was a decrease in mid expiratory flow. That means flow at low lung volumes. And this decrease was not temporarily, it was reported to remain even years after a saturation dive. It was concluded that there may be a long-term effect of cumulative hyperbaric exposure on the small airways function. These studies by Crosbie and colleagues have been published in the *British Journal of Industrial Medicine* and the JAP. They revealed that divers tended to have large lung volumes, greater then predicted. However, you have to know where the values are taken from. From what samples. What are the volumes that divers should have? It was found that the relationship of FEV_1 in percentage of vital capacity was decreased. Of course this is because of the large lung volumes. More recent studies of Davey and colleagues showed that indeed there was a decrease of the MEF_{50} and the MEF_{25}. More recent studies by Thorsen and C. Elliott published in 1990 at the EUBS meeting confirmed these findings.

Our own data

Now I would like to present some of our own data that we found in a cross sectional survey in a sample of 152 air divers and 28 oxygen divers. We have a small control group of subjects attending our institute for fitness to dive, but they had not dived before. Groups did not differ with respect to anthropometric data. Groups differed with respect to sports in that oxygen divers performed significantly more sports per week. Fractions of smokers and fractions of atopics did not differ. There were some differences but they were not statistically significant. The oxygen diving group comprised all combat swimmers of the German Navy available at that time. Compressed air divers were recruited from ships' diving groups. The arithmetic means of diving experience averaged 10.5 years and 7 years for oxygen and air divers, respectively. I only want to focus the attention on what we found when evaluating body plethysmography, spirometry, and CO diffusion as well as cold air challenge tests. Oxygen divers' and the air divers' MEF_{25} differed from the values of the controls significantly (Figure 12). You see a decrease of the MEF_{50} and the MEF_{25}. Please remember that groups did not differ with respect to smoking habits or

Details of Lung Function

	Air divers	*O_2-divers*	*Controls*
MEF_{50}[l/s]	5.39	5.12*	5.89
	(1.23)	(1.45)	(1.56)
MEF_{25}[l/s]	2.24**	2.10*	2.65
	(0.70)	(0.85)	(0.77)

Figure 12. Lung function of groups of air divers, oxygen divers and controls.

allergies. A stepwise forward multiple linear regression analysis showed a correlation between diving exposure—the index was years of diving—and some of these lung volumes. However, influence of age and stature on these variables was much stronger than years of diving. The MEF_{50} and the MEF_{25} were significantly inversely related to diving exposure, and the significance was higher than the influence of age on the decrease of these variables. These findings in compressed air divers may fit to the Norwegian findings in commercial divers, who performed deep saturation dives.

Histamine provocation

Figure 13 shows some results of another study that we performed. We did stepwise histamine provocation. You all may agree that there is a lot of controversy about the meaning of histamine provocation in the assessment of diving fitness. What you see is that there was a significant difference in the amount of divers (as a percentage on the Y-axis) that were hyper reactive to this substance and the control subjects. In this study we not only looked for smoking history—that by the way showed no difference between the groups—but also for allergy. We performed skin prick tests and there was no difference between the groups as well. Even in family history, there was no history of any kind of respiratory disease.

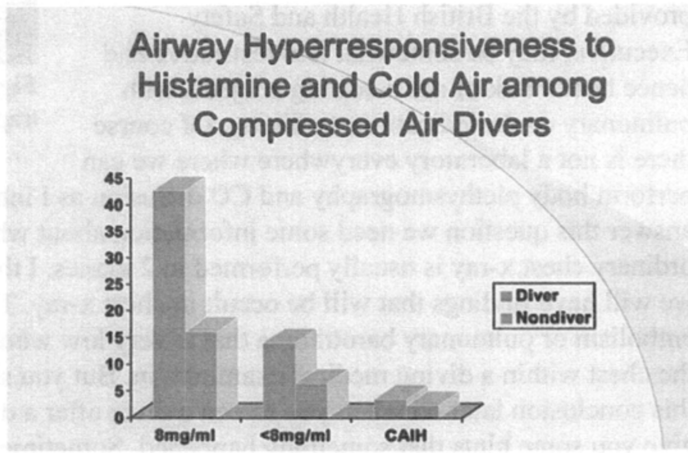

Figure 13. Airway responsiveness among air divers. Percentage of responding indi iduals are displayed on the Y-axis. Results for divers are depicted in the left sided columns.

CT of the lungs

In a small sample of this greater sample of our divers, we performed a high resolution CT of the lung to see what is going on inside the lung, "Are there any signs of small airways disease within this very sensitive method of evaluating differences?" Figure 14 shows the chest CT of a non-diver; this is a control subject. This is how it looks, deep inspiration and expiration, and that is the way it should look. Figure 15 is from a diver where we did expiratory CT. And I don't know if everybody can see it, but there are large areas of what we call "trapped air." This is how trapped air looks in a high resolution CT of the chest taken with deep inspiration. This technique has been used in the evaluation of patients with chronic

Figure 14. Normal chest CT of a non-diver.

obstructive pulmonary disease. The interesting finding is that there are subjects with air trapping.

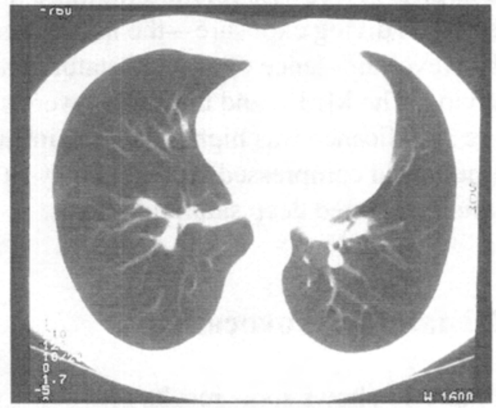

Figure 15. Chest CT of a diver, showing trapped air.

Pulmonary fitness to dive

What are the present criteria for pulmonary fitness to dive? I want to point out that I personally feel some doubt if the new criteria, especially those provided by the British Health and Safety Executive, may be somewhat less restrictive and hence bear a risk of not detecting subjects with pulmonary contraindications to diving. Of course there is not a laboratory everywhere where we can perform body plethysmography and CO diffusion as I introduced. What should be done? To answer this question we need some information about what could be performed. The ordinary chest x-ray is usually performed in 2 planes. I think I showed you that sometimes we will have findings that will be occult in chest x-ray. The total incidence of arterial gas embolism or pulmonary barotrauma that is very low would not substantiate doing a CT of the chest within a diving medical examination. But you should do it, and I will come back to this conclusion later on when you screen a diver after a diving accident. Medical history may give you some hints that something happened. Sometimes it is difficult to assess. We found subjects inside our group of lung barotrauma who had thoracic trauma in very early childhood, but often these data will not be known.

Pulmonary function testing

Pulmonary function testing should assist you in detecting possible deviations of ventilation. How about the value of spiro-ergometry? We talked about it in the morning. What is the meaning of maximum oxygen uptake? When you look into the book of Bennett and Elliott, you'll find a value of 3 liters of maximum oxygen uptake. But I think this is open to discussion. And I don't know if this is performed regularly. Dr. Faesecke asked me to provide some information as to what could be done on site. Most of you know that we are able nowadays to perform a lung function in an easy manner on site. We have peak flow meters, it's a very interesting thing, and they will monitor expiratory air flow limitation. Moreover we are able to get portable mini spirometers. I have brought one of these things with me. This is an electronic asthma monitor that allows you to perform and assess the complete flow volume loop. We currently use them to assess lung function of divers after open water dives on board ship after the dives. Of course, at the initial diving medical examination we should perform more sophisticated pulmonary function testing like body plethysmography.

Conclusions on pulmonary fitness to dive

What are my conclusions? The assessment of fitness to dive after pulmonary barotrauma should indeed include computed tomography of the chest. You may think that's natural, that's easy, but when you look into the literature, you will see that 5 years ago no one had performed it.

As I stated earlier, attention had been focused on radiological evaluation of the central nervous system only. We strongly recommend CT of the chest, preferably in the spiral mode, to be performed in any case of suspicion of pulmonary barotrauma. You should assess small airway function and look carefully at the shape of the flow volume loop. I think I am not the first to say this because I—unfortunately I could not attend the meeting held in Edinburgh in 1995—I read that professor Denison pointed that out in the proceedings.

I would like to answer the initial question by saying that you don't need to do another investigation of pulmonary function. All of you do is the spirometry but you should look at the shape of the flow volume curve and you should reconsider the MEF_{25}. And I guess it is not done everywhere.

Regarding the recommendations of fitness to dive, especially the civilian guidelines in Germany, there is nothing said about MEF_{25}.

Should we do chest x-rays in any case? It is very controversially debated. Looking at one of our latest cases of arterial gas embolism, one of our doctors was found to have a sarcoidosis of the lung. He was completely asymptomatic. The last chest x-ray had been taken 5 years ago and had been normal. Maybe I only stimulate the discussion by telling you this. The obvious tendency, especially in the HSE guidelines, is to drop chest x-ray from the diving medical examination, but I personally can not agree with this.

What is the value of graded bronchial challenge testing? I know there are some colleagues who believe that histamine is meaningless in evaluating the fitness to dive. You might assess airway hyper reactivity in exercise tests or cold air challenges. But if you are able to perform graded bronchial challenge tests, you may get information about the degree of hyper reactivity. A severe hyper reactivity on histamine or methacholine indicates that there is a strong tendency for airways obstruction. And so we think they are indeed meaningful. At least we think that bronchial challenges should be performed at the preliminary examination when starting a diving career that may last for forty or fifty years and will provide information if there is a risk of developing airway obstruction or small airway disease.

Neuropsychological and neuroradiological sequelae

The other thing I was asked to present was the neuropsychological and neuroradiological sequelae we found in our commercial divers. There is a very great discussion at the time on this question if there is evidence of brain damage in divers. So is there any need to do additional health examinations on divers? Of course we all know that when we are suffering from decompression illness, brain damage may be a sequela, this is not the question. But the question is: Is there any brain damage in divers who did not experience severe diving accidents? I think this was one of the studies that raised a wide spread discussion. This was performed by Professor Reul in Aachen and published in *Lancet* in 1995. He examined a group of 52 sports divers with a certain history of diving and 50 control subjects. What he found was a large amount of peri-ventricular white matter lesions in 27 divers and only 14 lesions in 10 controls. Moreover, there were cervical disc herniations in 32 divers and in only

9 controls. Three divers admittedly had suffered from DCS in that sample. And the conclusions that were drawn were that there may be brain damage in divers. Interesting was the criticism provided by Dr. Wilmshurst. He questioned what cervical disc herniations have to do with decompression illness because these structures are very scarcely perfused. Moreover, a Dutch group suggested that the control subjects should have been recruited from divers with little diving experience to rule out the possibility that the decision to start diving is the first sign of brain damage and I think that is good.

Kari Todnem of NUTEC explored commercial divers, saturation divers. They performed very sensitive psychometric testing. Of course there were a great number of divers who had suffered from decompression illness. But what I think was very interesting, is the apparent contradiction to the findings of Reul and colleagues with respect to the MRI findings. In a sample of 37 divers versus 49 controls there were lesions in 19% of the divers versus 42% of the controls.

The meaning of brain lesions in MRI

So what is the meaning of brain lesions in MRI? Fueredi and colleagues investigated 19 compressed air workers and 11 age matched controls. They found a large amount of brain lesions in the compressed air workers versus 2 of the controls. None of these studies revealed a correlation between brain lesions and diving indices. Another study which led to wide debate last year by Knauth and colleagues was published in the *British Medical Journal*. They investigated 87 sport divers with a certain diving experience and they investigated PFO (patent foramen ovale). They found that 25 had a right to left shunt. Seven subjects without PFO had 7 peri-ventricular white matter lesions on MRI scans. They concluded that the prevalence of multiple brain lesions is significantly higher in divers with a PFO. However, the prevalence of these lesions when you compare those with the PFO versus those without PFO, there was no significant difference. Now, about 25% of the normal population is known to have a PFO and all of us know the incidence of decompression illness, it's 0.04%. So what's the meaning of a PFO? Dr. Wilmshurst was the first who reported that in compressed air divers with a history of DCS, compared to those without DCS, there was a high incidence of PFO.

Animal data

Now in this context I like to show you some of our latest data that we detected in an animal study. We performed this study to detect findings in the lung after provocative dives. We let pigs perform a dive to 50 msw. The bottom time was 19 minutes. Time of compression took 5 minutes and time of decompression took 3 minutes. This was a schedule that was completely matching to a schedule

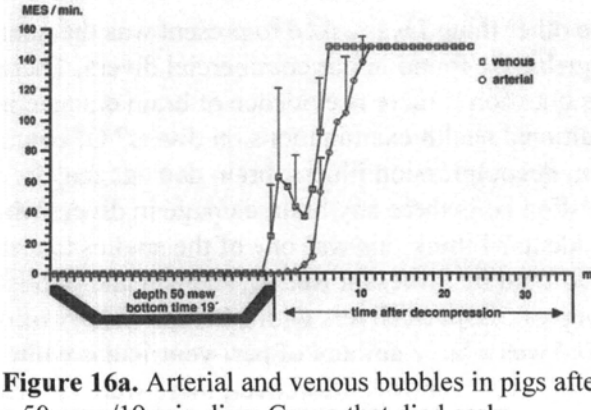

Figure 16a. Arterial and venous bubbles in pigs after a 50 msw/19 min dive: Group that died early.

introduced by Dr. Broome and published 2 years ago, who did this at the Navy Medical Research Institute to evaluate neurological decompression illness in pigs. The reason for presenting these data is to show you what we found by transcranial doppler ultrasound of the arteria carotis and of the vena jugularis. This is in addition to the distribution of arterial bubbles that we detected in the arteria carotis communis and you see these 2 groups of pigs, those who died early in Figure 16a and those who were dissected 3 hours after the dive in Figure 16b. Three minutes after venous gas embolism, a very high amount of arterial gas embolism is evident, that may raise the question about the meaning of a PFO, since autopsy revealed no PFO in any of these pigs. I guess there are extracardial shunts that may open under certain conditions.

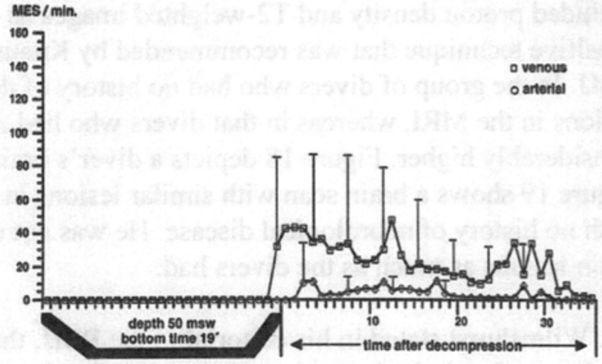

Figure 16b. Arterial and venous bubbles in pigs after a 50 msw/19 min dive: Group of animals that were dissected 3 hours after the dive.

Figure 17 shows the CT of the lung of one of the pigs that performed the provocative dive and it was very interesting for us to see this picture. Even our radiologist has not seen this picture before and I don't know if these pictures exist in the literature. There are large amounts of gas, caused by venous gas embolism after this dive (19 minutes bottom time at 50 meters) which was not far away from what is done in recreational diving. These images indicate why the animals died.

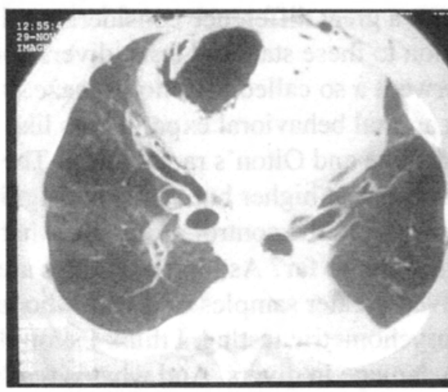
Figure 17. CT of pig lung after VGE.

Brain lesions in commercial divers

In cooperation with Doctor Faesecke we investigated some of our German commercial divers using MRI and psychometric testing. There was a strong selection of this sample in that these divers had a diving experience of at least 500 hours of diving. Twenty-seven divers were compared with 20 control subjects matched for age and smoking history. No one had a history of neurological disease. There were no differences between these samples in alcohol drinking habits. Diving exposure ranged from 579 to 38,000 hours of diving with an arithmetic mean of 7,500 hours. The mean maximum depth was 63 meters. Only 5 divers had experience in saturation diving. We found something very similar to what was found in Norwegian commercial divers that performed

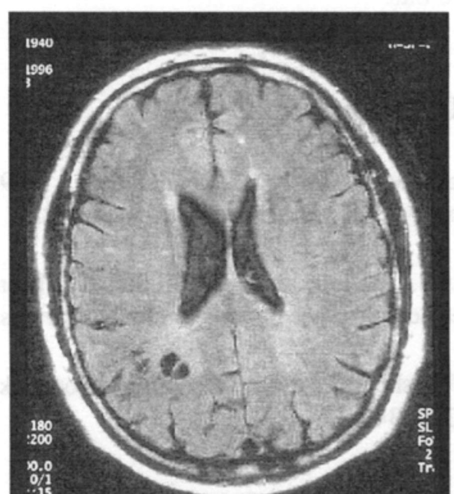
Figure 18. Brain MRI of a diver, showing white matter lesions.

saturation diving: There was no difference between divers and controls. The MRI protocol included proton density and T2-weighted images as well as turbo FLAIR sequences, a new sensitive technique that was recommended by Knauth and colleagues in their study in the BMJ. In the group of divers who had no history of decompression illness, only 26% had lesions in the MRI, whereas in that divers who had a history of mild DCS this prevalence was considerably higher. Figure 18 depicts a diver's brain scan, showing white matter lesions. Figure 19 shows a brain scan with similar lesions in a control subject who was born in 1960, with no history of neurological disease. He was not drinking too much alcohol. He had these brain lesions as much as the divers had.

Dr. Wilmshurst stated in his editorial in the BMJ, that evidence of pathological change is not proof of function deficit. And so we have to ask, what is the functional deficit? We performed a conventional test battery of psychometric testing like the Rey-figure copy, Rey-figure delay, Buschke's selective reminding test, symbol digit modality test, trail making test A and B. The only significant difference was a higher amount of failures in the divers' group compared to the control group, but it was only of very mild statistical significance. And there was not a great difference considering all these tests. In addition to these standard tests, divers and controls underwent a so called locomotor maze. It was derived from animal behavioral experiments like the Morris water maze and Olton's radial maze. The sum of errors was somewhat higher but it was not significantly different from the control group. So what are the conclusions so far? As long as studies are lacking that involved greater samples of divers who underwent MRI and psychometric testing, I think I should answer the question that there is no evidence for brain damage in divers. And what is really true is what Prof. Elliott wrote in *Pressure* last year that the risk of long term brain damage is more likely to occur once the diving is over at the bar.

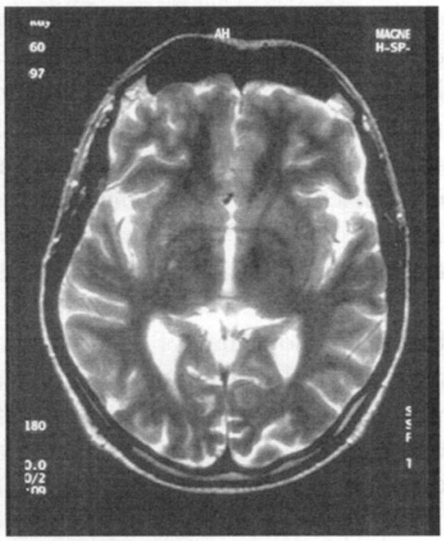

Figure 19. Brain MRI of a control subject, showing similar white matter lesions.

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DISCUSSION AFTER DR. TETZLAFF

Unidentified speaker: In reference to Figure 10, how could he be declared fit to dive with this MEF_{25}?

Dr. Tetzlaff: MEF_{25} in Germany, and I think in most of the European countries, is not assessed for fitness to dive. You can have a complete normal FEV_1 and a subnormal MEF_{25}. Yes, that is exactly the problem I wanted to show.

Unidentified speaker: Sorry, but what was the time between pre- and post- entry? Was it within a year or within a month? You had a pre-entry lung function test and a post-entry lung test. What was the time between those two?

Tetzlaff: Pre-entry lung function, I don't know exactly but I think within one year before the incident, and post-injury lung function was about two weeks after the incident.

Dr. Pieter-Jan van Ooij: Is it your recommendation to make a CT scan of the lung of every diver?

Tetzlaff: No, you misunderstood me. We are talking about recreational diving, too. In Europe there are now about 4 million recreational divers. It is a rising industry. You may be asked whether an injured diver may return to diving. When there was a diving accident comparable with pulmonary barotrauma you should look at the lung and not only at the brain. A lesion in the brain will not necessarily say anything about further fitness to dive. Chest x-ray may not be sensitive enough to evaluate pulmonary lesions in the case of pulmonary barotrauma. And so my message was that you should investigate CT of the chest when there has been a case of arterial gas embolism. Because we all know it is a clinical diagnosis.

van Ooij: O.K. We found some pulmonary function cases. We also looked to see if there is a pressure relationship between those CAGEs and the pulmonary function?

Tetzlaff: How is it pressure related?

van Ooij: People who dive deeper have more CAGE.

Tetzlaff: It is a great problem to evaluate how deep people dive. We tried to separate some depths as you could see in this study concerning our brain. But it is very difficult to get these data. In military diving we performed our cross-sectional studies exclusively for military divers. There is a diving range where they are allowed to dive, between the surface and 50 msw. But there is no information provided about how much time they spent at the depths. I talked to Doctor Faesecke who agreed that presently no one has a formula to detect real diving exposure that will enable you to tell at what time, at what depth and what partial pressure the divers are, and what the impact of this is on lung function. There were some previous studies, where a relation was found between changes in pulmonary function towards maximum diving depths. Diving years was a diving index which correlated with changes in pulmonary function more consistently.

Dr. Wouter Sterk: I have some questions. I saw that the bronchial challenge test in your divers showed a much higher figure who responded as compared to the control. Did it differ at the entry when they started as a diver, or are asthmatics more prone to become divers in the navy? In Holland we do the same kind of testing as you do, at the Diving Medical Center as well as at my hospital. So we also look at the flow volume curves and do bronchial challenge tests. And I think it is very useful. But in your sample was it a disproportion or is it just the diving years that made them more responsive to histamine?

Tetzlaff: There was a very slight correlation to the number of dives and the degree of airway hyper responsiveness. And the prevalence was very high. It was even higher than in the normal population. It was about 40%. We have about 2,500 fitness examinations a year and I frequently found these flow volume loops with the decreased MEF. What I did not present to you up to now is that there were some subjects reacting to cold air challenge (3 minutes of iso-capnic hyperventilation). And these, you will agree with me, are subjects that should not dive.

Sterk: What about the challenge test? Do you accept for entry somebody responding to 8 milligrams of histamine per milliliter?

Tetzlaff: Yes, at the time we think that a mild degree of airway hyper responsiveness is no contraindication for diving. And the problem is that we are talking about limits. What is the limit? I think it may be 2 milligrams per milliliter indicating that below that value this is a highly hyper-reactive subject.

Dr. Karl-Peter Faesecke: I am positive at 8 mg, too.

Sterk: Yes, I think so. So am I.

Tetzlaff: Many smokers dive, there may be a relation.

Sterk: You have to be crazy to do both, I agree.

Dr. T. van Rees-Veiling: I have a question about the MEF you're talking about. Do you know something about the standard deviation?

Tetzlaff: Yes, certainly, there are recommendations of the European respiratory society. And they are distributed, I don't know the exact figure, but they have to be within 5%. They are recommendations for normal people. And the MEF should reach values above 80% of what is predicted.

Dr. Jan Risberg: I believe you are very wrong in that statement. As far as I remember, the standard deviation for MEF and the low expiratory, the flow rates at mid-expiratory levels have a very large variation. In contrast to the FVC and FEV1, which is rather small.

Tetzlaff: Much larger, you're right, but it is not 40%. And this is the value we found.

Risberg: Possibly not. But we should in my opinion accept two standard deviations. Which I believe is in fact larger than 17%.

Tetzlaff: You are right but it is not above 20%.

Risberg: I cannot recall; it is larger than 2 SD.

XI.
TRIMIX OR SATURATION?

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Introduction

The limits of compressed air work in tunneling: Is saturation a feasible method for greater depths and how would it work?

You all know what trimix is—a mixture of nitrogen, helium, and oxygen. In the beginning of the 1980's we started to use trimix in commercial diving operations, particularly in the Middle East, at depths between 50 to 100 msw. It was very simple. We used air and compressed it to 50 msw, then we added helium to get the desired depth, put it all through a compressor again, and we had a trimix.

Later on we started to use trimix in a more sophisticated way, mostly as a pre-fabricated mixture. For a maximum diving depth of 50 msw we used 25% oxygen, 25% helium, and 50% nitrogen. In deciding what mixture to be used we considered several things.

Trimix development

Oxygen limits

First of all, consider the limits to oxygen as summarized in Table 1. The maximum oxygen partial pressure during diving or hyperbaric work should be around 1.5 bar to avoid acute oxygen toxicity. As I explained before, to prevent long term oxygen side effects the Cumulative Pulmonary Toxicity Dose (CPTD), or as Hamilton calls it Oxygen Toxicity Units (OTU), on a working week basis has to be considered.

- ➔ PO2 ≤ 1.5 bar
- ➔ CPTD on a working week basis:
  - –Max. 450 CPTD per day
  - –Max. 2500 CPTD per week
  - –Max. 4500 CPTD per two weeks

Table 1. The oxygen limits

So that is one thing which led us to take 25% oxygen for diving up to 50 meters.

Nitrogen limits

Figure 1. Trimix experiments at Hakodate, 1989 - 94.

Then, of course, there is the nitrogen part where we want to avoid nitrogen narcosis as much as possible. Depending on the purpose of the dive, or the caisson work, we decided that the maximum partial pressure of nitrogen should be somewhere between that on air at 30 to 40 msw.

The third thing that we looked at, depending on working time and exposure time, is which combination of gases gave the shortest decompression time; which was most economical. Furthermore the composition as I showed you also has the advantage that communication is possible without helium speech unscramblers. There is a little cracking in the voice, a little bit of Donald Duck, but that's okay, it is perfectly understandable.

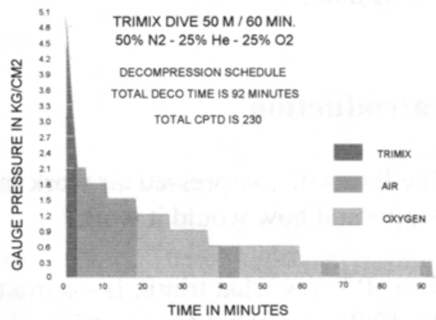

Figure 2. Decompression schedule for trimix dive 50 msw / 60 min.

Trimix experiments

Now we come to the trimix experiments in Japan which were performed between 1989 and 1994 (Figure 1). I developed some decompression schedules for that. First we did a 50 msw dive (Figure 2), that is to say an exposure in the chamber, compressed with air, with the divers on full face mask breathing trimix. We took 60 minutes bottom time because it was thought that working in a real situation, such as in a caisson, would be limited to only light to moderate work of short duration because it would only be for inspection and some minor repairs. You can see that for a 60 minute exposure we had a little bit more then 90 minutes of decompression time which is shorter than on air I can assure you. From 50 msw to the first stop at 21 msw we changed to air breathing again and then from 12 msw on to oxygen in 20 minute cycles interrupted by 5 minutes on air. This went successfully with 6 divers. No bubbles were found either by doppler or by echocardiography and, I have to add, during the exposure time in the chamber there was also some mild exercise done on a small bicycle ergometer. No bubbles.

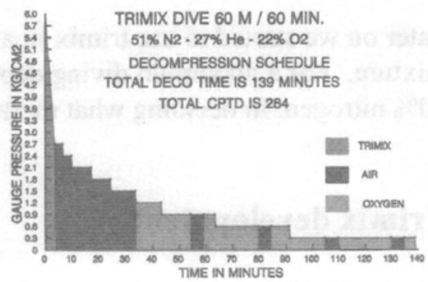

Figure 3. Decompression schedule for trimix dive 60 msw / 60 min.

So the next thing was to go a little bit deeper, 60 msw (Figure 3). Then you see that the total decompression time is nearly 140 minutes already. The CPTD is nice in that range but we had to reduce oxygen a little bit, of course, and we had to increase the helium a bit. This also worked fine; no bubbles found in this series.

Later on we did a 70 msw dive, 60 minutes, 6 divers again, and then you see that the total decompression time is over 4 hours, CPTD is approaching the limits, oxygen is a little bit more decreased, helium has gone up a little bit (Figure 4). This makes it quite a severe dive, I think, in terms of decompression time needed. So at these greater depths, approaching 70 msw or beyond, we should limit the bounce dive exposures, if I may call it so, to about 60 minutes. And with robots doing the work inside the compressed air environment that would be perfectly feasible if the robots do their work properly. In these six divers we had some bubbles, Grade 1 in one diver, that's all.

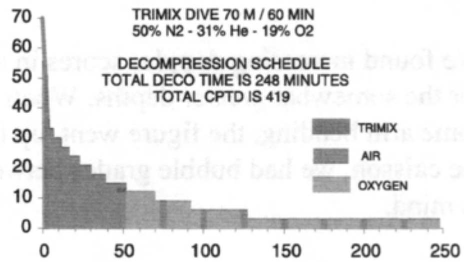

Figure 4. Decompression schedule for trimix dive 70 msw / 60 min.

Trimix in practice: The Nagoya project

We were very pleased and thought "Let's give it a go" at the Nagoya project (Meiko West Bridge construction) in 1995 which was supposed to go to a maximum depth of 45 meters. A series of tables were made for that purpose with total exposure times up to two hours. Figure 5 shows the caisson next to the old Meiko Bridge. The purpose was to construct foundations to enable building a parallel bridge. This required careful operation in order not to cause damage to the old bridge. As said before, the digging was done with robots (ROVO) but inspection and repairs required human intervention under high pressure. The results were as follows:

Decompression illness

The maximum depth appeared to be 42 msw. Between 30 and 42 msw we had 1,053 trimix exposures. Yesterday Dr. Nashimoto said there were no cases of DCI but he added "that required decompression therapy." There were in fact 11 cases of DCI which we found out about because there was a doctor on the site most of the time. There was a lot of talking with and examination of the divers. We had to do the doppler measurements and we heard of cases of DCI. At least three of them were because of procedural errors. There was one case which was a very good demonstration of what we should look for if we want to decrease the number of DCIs. That was an incident in which the divers, the crew, were brought up from the first stop, somewhere around 21 msw or so, by accident directly to the surface. Then the supervisor, the man in control of the panel who was obviously not properly trained and did not know what to do, hesitated quite some time, then took them down again after about 8 minutes to the first stop or somewhere near it, and there resumed the decompression profile, which obviously was a very wrong procedure to do. Other mistakes were also made even though there was a very nice, sophisticated computer program showing the decompression profile to the chamber operator, showing him where he was. There were warnings in Japanese when they had to get to the next stop and whatever. A very helpful program but even then some people just can't read or understand their own language. We should be aware of that.

Figure 5. The caisson next to the Meiko West Bridge at Nagoya, Japan.

Bubble counts

We found increasing doppler scores in about 46% of the men's exposures at rest, particularly for the somewhat greater depths. When we let them do some exercise, 3 deep knee bends and some arm bending, the figure went up to 62%. And, particularly at the maximum depth of the caisson, we had bubble grades between 3 and 4 which are quite high and not what we had in mind.

There were two reasons for it. First, the tables were designed for light to moderate work. Well, it happened to be very heavy work. We also had pulse frequency measurements which showed pulse frequencies of up to 170 - 180 per minute for a prolonged time, which is quite something. In between we had some disasters with the machinery that had to be repaired extensively and at the end the machinery had to be removed from the caisson because it was too expensive to leave there. That was a real heavy job, much too heavy. I think we should think about other methods to do that.

Another thing that we found is that people over 40 years of age had higher bubble grades. There was a significant relation between age and bubble grade. And, of course, we also had some high bubblers and some low bubblers. In total there were 45 different people under pressure during this project. Some of them bubbled all the time and others didn't. But the older ones, and we had older engineers, 50 plus, inside because of their experience, were more bubble prone although they did not complain about decompression illness.

Reporting symptoms

There is the problem of reporting symptoms. To confess to a doctor that you suffer from niggles is something. To tell your boss or supervisor that you had niggles, which might need some therapy, is something different. And in this situation they preferred to have a little bit of pain. I know of at least one diver who compressed himself at night in a small chamber, and he treated himself on a "wet finger way" but, o.k., he got away with it. All of these cases were, let's call them Type 1 niggles, some bends, some skin bends. There was one case related to the accident during decompression omitting stops that I just described with definite neurological symptoms. It was a compromised dive so we shouldn't be surprised but even he did not want to be treated and after some days the symptoms were gone and they just continued to do their job. So is recompression treatment really needed I would ask? I would prefer so, but okay.

Recommendations

My recommendations are summarized in Figure 6. Based on our experiences so far, as I lined out yesterday and I want to do it once again, is that of course we should use air, particularly for compressed air work shallower than about 30 msw. And in this range we should also consider the use of enriched air nitrox. This is not a golden rule, it is only a guideline. And we should not, I think, decide

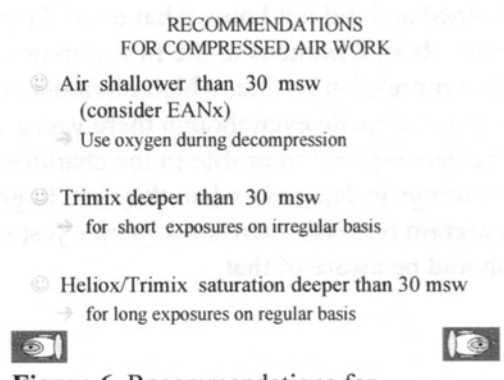

Figure 6. Recommendations for compressed air work.

on rules here but on guidelines only, which can be flexible depending on the project. And of course oxygen is necessary during decompression, there is no question about that. If the operation goes much beyond 30 msw I think for short exposures on an irregular basis we should consider trimix. Trimix needs a more complex setup, the gas lines are more complicated, the gas switches are more complicated. So the decompression profile should be observed closely in a professional way and preferably you should also do it by computer guidance just to avoid human errors. And then if there is a long exposure to be expected on a regular basis, when there is a breakdown of machinery which needs, let's say a week or two weeks of regular daily work, then in my opinion you can use trimix or heliox saturation.

Decompressie-tabellen voor het werken onder overdruk (caisson tabellen).
Drukken zijn weergegeven in BAR overdruk, tijden in minuten en tienden van minuten.

MAXIMALE WERKDRUK IS **3.0 BAR.**
Opkomstsnelheid is maximaal 1 bar/minuut.
De stoptijd gaat in na aankomst op de betreffende stop.
HERHALINGS-INTERVAL IS 16 UUR.

Code: cox16
Copyright dadcodat 1998

tijd op druk (min.)	tijd tot 1ste stop (min.)	Stops: overdruk in BAR										totale decom-pressie tijd (min.)	totaal UPTD
		1.5 lucht	1.5 oxy	1.2 lucht	1.2 oxy	0.9 lucht	0.9 oxy	0.6 lucht	0.6 oxy	0.3 lucht	0.3 oxy		
7	3.0	GEEN STOPS										3.0	-
30	2.1						5	-	5	-	5	18.0	51
60	1.8				10	-	10	5	-	-	20	48.0	125
90	1.8				10	-	10	5	20	5	20	73.0	185
120	1.8				20	5	20	5	20	5	25	103.0	266
150	1.5		10	5	20	5	20	5	20	5	35	128.0	334
180	1.5		10	5	20	5	20	5	20	5	60	153.0	393
210	1.5		10	5	20	5	20	5	45	15	50	178.0	448

Figure 7. Dutch (DCD) decompression table for caisson work to 3 bar.

If we look at the Dutch (DCD) decompression table for caisson work to 3 bar gauge in Figure 7, you can see that for a 210 minutes exposure, 3.5 hours, you have about 3 hours of decompression time and I think that would be the maximum. But with trimix you can shorten it considerably. This is shown in Figure 8 for a 120 minute exposure to 3 bar gauge. If you look at the dotted line, which is the air table that is only used as a backup in case of oxygen failure, the decompression time is over 3 hours. If oxygen is used during decompression (solid line) you have a little bit over 100 minutes of decompression time. If you go on a trimix, you end up with a 60 minute decompression time and that is something to keep in mind. But you must look at the project and see if it is worth all the extra effort and all the extra techniques. And, of course, the cost also plays an important role. But in my opinion as a doctor, the workers come first and the cost comes last. But managers don't always agree with that.

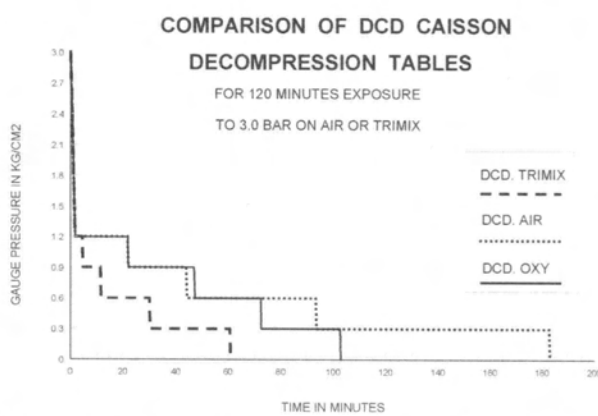

Figure 8. Comparison of DCD air, air and oxygen, and trimix decompression schedules for an exposre of 120 minutes to 3 bar gauge.

XII. SATURATION

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Introduction

There have been so many critical points, but I would just like to say that in my opinion this is the future. I have not come to try to defend the dinosaurs, but this is a dying method of diving, very expensive. I do believe it had its time for quite some years, but I believe it will be less and less used for diving. I could think of no better way to tune everyone in than to talk about what it requires to do saturation diving. I am not discussing details or what tables to use.

The main principle: You do the compression phase to about 10 msw and you do your system check, whether you use air or helium. Then you complete the pressurization to storage depth. Usually storage depth will be equal or, if it is supposed to be more cost effective, somewhat shallower than the depth where you are actually going to work.

When you do diving, you lower the diver from the diver platform in the diving bell, doing a "bell run," which has a certain limit of exposure. The diver swims out of the bell and does the work. And you can keep the work site at a different pressure level than the storage depth, requiring an excursion. The diver swims out from the bell to a shallower or deeper pressure to do the work.

The decompression is usually done in a linear manner with either a continuous bleed or, if you don't have the facility for that, you do it in a staged way by doing one or two fsw. In Norway and some other places you make night stops, because we don't think it is physiologically sound to decompress during the night. Whether this is correct or not is open for discussion. Ascent rate to the surface is dependent on diving pressure. The deeper you start the slower it has to go. And it goes slower as you reach the surface.

Saturation diving in caisson work

Basic requirements

When doing saturation diving with caisson work we need a lot of hardware if we are to keep up the safety level that we are used to with saturation diving. You need either a multicompartment chamber system or a total crew rescue chamber connected if you want to deal with the fire hazard, in my opinion. If you get a fire in that chamber you need to evacuate the people and you can evacuate them in another chamber on site if you have some rescue chamber facility to take them away. And that is expensive. You need primary and secondary gas supplies. You need secondary power. And you need a life support package to take care of the people if you evacuate them. So, in fact, you need both primary and secondary life support. You can do this differently if you do it with air saturation, covered later. But with deeper air saturation it is really hardware intensive.

It is expensive, at least if you are going to use helium. The price is about 11 DM per cubic meter. You need some CO_2 adsorbent. And you need power for your life support unit (LSU). Even more important you need the human resources to run a saturation operation. Probably three shifts: A diving/life support supervisor, technician, and a diving technician/gas man.

Experience with air saturation

What is the experience? As you are probably aware, I am the Norwegian "expert" on air saturation as well since I know of only a single real air saturation having been done in Norway. I believe there may be a couple more but there are very, very few being done in Norway. In the NOAA manual (1991), which I tried to scan, I counted 50 experimental air saturation dives, which implies that there must be a number of other operational saturation dives, but there are not many. There is a minimum of industry practice in this area. I think one of the people who could tell us about this is Bill Hamilton, so you can comment on it later on. If you go to the literature, it says that if we go for air saturation we should limit storage depth to about 15 msw. If we want to avoid all the effects on the lungs and everything, we should keep PO_2 at 30 to 50 kPa. If you go for normoxic nitrox mixtures limit maximum storage depth to 37 msw. This imposes quite some limits.

Experience with heliox saturation

If you go for heliox saturation, Bennett & Elliott (1993) counted 65 experimental deep dives. There have been thousands of operational saturation dives since Bond started it in the US Navy in 1962. We know that heliox saturation is safe. DCS incidences are almost zero wherever you go: Brazil, the U.S., the U.K., Norway, and France, of course. It does not seem to depend very much on the table views. The method by itself seems to be safe. Maybe because it requires so much in the way of personnel and resources. Since you get the best divers, you get the best technicians, the best organization; that maybe part of the explanation, I don't know.

Alternatives

If you decide to go for a working depth of 60 msw, you have some different possibilities. When you go for air (or nitrox) saturation, you can choose the CIRIA tables from 1985 which will allow you a storage of maximum 40 msw (Hennessy et al, 1985). If you go for a downward excursion to 60 msw on air, you are supposed to limit that to four hours. There is supposed to be five hours between these excursions if you stay at 60 metres for 1 hour, and 10 hours if you stay there for 4 hours. You should hold at storage depth12 hours before the start of decompression. And you need, according these tables, 4 days and 14 hours decompression time, a significant time to get the personnel out.

Or you could choose the NOAA air sat table of 1979 if you go for maximum storage depth of 36 msw. You could do that but recommended maximum storage depth is 31 msw. The maximum period you can stay at 60 msw if you come from 31 msw is 40 minutes. And there should be 6 hours between those excursions. You should stay there 30 hours before you start decompression. And according to these rather fast tables it would require, I would say, 31 hours decompression time from 31 metres, I believe.

Some other alternatives. If you choose the US Navy heliox saturation table you can do a 20 msw unlimited downward excursion from 40 msw. It's a rather tough excursion in our opinion, as we have examined the amount of venous gas accumulation with Doppler during the excursions from different depths. But anyway, if you stick to it, the holding time before you can start your decompression is not specified, probably not required. You can go immediately from the downward excursion to the start of decompression. And decompression time from 42 msw to surface is 2 days and 13 hours.

If you go for the Norwegian decompression tables from 1991 (NPD, 1991), they won't allow more than 8 msw downward unlimited excursion. If you start from 54 msw, it will take 3 days and 16 minutes decompression time.

[Editors' note: NOAA has a comprehensive set of air saturation and excursion tables developed in the Repex program but not included in the NOAA Diving Manual (Hamilton et al, 1988). Both excursion and saturation decompressions were tested with Doppler.]

Problems associated with saturation diving

There are some problems associated with saturation diving. We know from our experiments and other experiments that pulmonary effects can be observed in saturation divers. If you go for air saturation of course you are exposed to the possibility of nitrogen narcosis. The question of decompression sickness is a significant question if you select one of the tables that is not being used frequently. And that I believe would go for the air saturation tables. They are not in industry use today, so they are historical data now.

To minimize the problems with oxygen toxicity you should, according to available literature, keep PO_2 lower than 50 kPa which would make air saturation only acceptable to 15 msw. But higher PO_2 is acceptable during lockouts and parts of decompression if you can reduce other medical problems like decompression stress, i.e., venous gas emboli or risk of hypoxia.

We know that venous gas embolism has been extensively demonstrated during decompression, both in surface-oriented bounce dives and saturation dives. Venous gas embolism has been observed after ascending excursions from 7 msw using air, and we have observed it with ascending excursions from 5 msw to surface using heliox. So doing saturation diving with excursions will impose the problem of venous gas emboli. We should be careful selecting procedures that are reasonably good and tested for that purpose because we know the amount of venous gas emboli has been shown to correlate with the reduction of TLCO (Thorsen et al, 1994; 1995) and the risk of decompression illness (Sawatzky, 1990).

That is a co-variation. I don't say it is a cause and effect relation between decompression illness and venous gas embolism. The means of reducing venous gas embolism would be to decrease the ascent rate and extend decompression stops which, of course, will make the tables less practical and more expensive.

You can increase the PO_2 in which you have to pay to the lungs. And we can decrease the excursion range, adjusting the storage depth closer to where we want to do the work.

Concerning the decompression tables, none, as far as I know, of the decompression saturation tables have been tested acceptably with Doppler, that is, on a great scale. There have been a number of tests on them but not to the level of which the US Navy air tables or the DCIEM tables have been tested.

Excursion limits have not been tested acceptably with Doppler so we don't know for sure that we don't cause health effects by using this method. But of course the statistics are good. We have almost no decompression illness. If you choose to work with heliox saturation we believe that there is less decompression stress which means the tables have been shown to produce very little decompression sickness. There is no risk of nitrogen narcosis and there is minimal hyperoxic stress if we choose the available tables.

There are some medical disadvantages if you choose air saturation. Concerning once again decompression stress and hyperoxic stress and pulmonary effects, saturation diving is resource intensive. Concerning hardware, personnel, knowledge, consumables, it seems to be safe at least if used according to "industry standard." It is a viable alternative for extensive work projects, that is, projects when you anticipate a lot of diving. And for that purpose, and for that purpose alone, I think it should deserve a place.

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DISCUSSION AFTER DR. RISBERG, SATURATION

Mr. Jean-Claude Le Péchon: On details of procedures, there are many schools and there are many small details that can be discussed. But I don't want to go into these figures.

One point is these CIRIA tables; I avoid them very carefully.

A second point is about going to heliox. You presented a plan using compressing on air to 10 msw as a possibility. If you are thinking of a saturation in the range of 30 msw you are likely to be on a very nice trimix. You will have half nitrogen in the mixture; half helium and half nitrogen.

Dr. Jan Risberg: You misstated something; air compression would be for air saturation.

Le Péchon: No, even for heliox saturation, the US Navy learned some time ago to establish the PO_2 by compressing with air to 10 msw and then adding the extra heliox. If you go to 100 msw there is a little nitrogen in there, it's negligible. But if you go to 30 msw then you are on a nice trimix. Then when you start work you should also use a trimix. And then for shallow water using heliox you are very close to trimix if you compress on air to 10 msw.

Concerning nitrox saturation, there is probably more experience than you have reported. And for information I've organized probably one of the first saturations offshore on nitrox in 1982. We saturated 36 people in a nitrox saturation to a diving range of 30 msw. This was part of our program in nitrox saturation and it was uneventful all the time. So we have very sound decompression tables for nitrox saturation in the range 50 to 60 msw on air, with lockouts on air and having an appropriate mixture in the chamber. So there is probably more experience than you have reported.

You mentioned the fire risk inside the chamber. When you are in heliox, even in the range of 20 msw, the risk of fire is extremely small, because the heat exchange in helium makes nothing burn, even with a partial pressure in the range of 0.4 Bar, except at the end of decompression when you reach the 10 msw range.

The risk in our operation is fire in the tunneling machine where you may have to evacuate. Everybody is concerned about the chamber, but if you are in saturation I would not be very worried about a fire risk inside, but outside. Evacuation still is needed. But it is a different issue to evacuate the tunnel than to evacuate the chamber. Both are dramatic but it is not the same type of safety rules that you have to use.

Then you say that bubble doppler data in saturation is missing, I think there is a lot of this data also, and I can also say that the first saturation that was monitored with the doppler system was in 1975, it was carried out by Mazurel. It was a 300 msw dive for which I was responsible. This was the first time that saturation decompression was monitored throughout the decompression with a bubble detector. And Mazurel after that has followed almost all saturation experiments. So there are hundreds of saturation dives monitored from the beginning to the end with doppler. So there is a lot of data. Now of course if we need long exposure and if we could bring the system in some way to transfer the people under pressure in the tunnel that might be in favour for heliox.

Risberg: I have some comments. Concerning the nitrox exposure I would expect that someone knows about that because it has been done. But it is not readily available. It is not widely reported in the open scientific literature. When evaluating the tables, it is hard to evaluate something that is not readily available, and that was my point.

Secondly, we talk about the fire risk. The risk is the product of probability and consequence. The fire risk concerning the probability of the fire in the chamber is definitively little. But I can not agree when it comes to the consequences. If you have a fire in the saturation chamber you need to evacuate the crew to another chamber or to an evacuation capsule. That would be my safety requirement for doing saturation diving.

Of course there have been a lot of experimental dives doing doppler monitoring. But testing decompression schedules, saturation decompression schedules has not been done on the scale as we have done for air bounce diving, regular air dives. It is out of proportion, they have been done in comparatively small numbers.

Le Péchon: If you have a fire in the chamber, wherever it is, you don't need to evacuate people, you need to kill the fire before the fire kills the people. There is no time and no choice. Inside the chamber is a fire extinguisher that will solve the problem. It will always be too late for evacuation.

Dr. R.W. Bill Hamilton: It is nice to be able to get out. I don't think you should take the fire risk lightly when your compression is with air. If you have a normal saturation where the PO_2 is reduced, you don't have a fire risk at all. You don't need to evacuate or anything else. You won't have a fire. But if you have air in the chamber, let's say 3 bars, 30 msw of pressure, that's deeper than we can go with air saturation. The deepest is about 15 msw. But at 15 msw the burning rate is substantially higher than on the surface. You can have a fire, but you can deal with it. You can deal with the fire. It doesn't explode, it just burns rapidly. You can deal with the fire and you must be prepared to do that. You need training to deal with the fire and the apparatus to deal with it. It is too risky to do it otherwise. The fires that have happened are almost always associated with an oxygen leak, and usually with an ignition source that is in violation of the rules.

You reported a maximum excursion from 31 msw to 60 msw was 40 minutes (NOAA Tables). But that's the Navy unlimited duration tables. With Repex procedures you can make timed excursions for 4 hours more or less depending on the exact saturation depth.

Could you tell us why the CIRIA tables are no good? What about them?

Le Péchon: They have pressure drops of 5 msw, that's it. Any change of pressure is a stress if you have a continuous bleed, whether linear or not. These are the small things I don't want to discuss now. But if you have stops like that, that's necessarily wrong. If you read the paper which was at the origin of those tables, they made the thing exactly the wrong way. Making stops of 5 msw is wrong. Whatever the PO_2, you don't need to stress people like that.

Dr. Wouter Sterk: I agree fully. You know where the 5 metre stops originated from: England at last went metric. That's it. It was already in 1972 with the CIRIA tables for diving on the North sea. It is crazy.

Hamilton: The tables you're talking about are done by Hempleman.

Sterk and Le Péchon: Yes.

Le Péchon: And when they were published we were very worried that they would become required in the U.K. And I personally wrote to Jacky Warner telling him if you ask us to that we shall not. We shall never do that.

Risberg: Just for the record, it is 5 fsw, not 5 msw.

Le Péchon: Then it has been changed, originally it was 5 msw.

Hamilton: There were two sets of CIRIA tables. You may be thinking about the first set.

Le Péchon: So I have to modify my statement. The early ones were 5 msw and since then I've never looked at the new ones. So I apologize about what I said before.

Sterk: Also for the record. Are you talking about nitrox saturation or heliox saturation?

Le Péchon: Heliox.

Sterk: And you are referring to the nitrox saturation which is different. And I'm sure that in heliox tables they have 5 metre steps.

Risberg: But no one will use these CIRIA tables.

Sterk and Le Péchon: But at that time they were using them!!!

Dr. Anthony Low: I wonder if you could comment on saturation diving and diving tables with nitrogen/ oxygen. I am not quite sure whether you have the information of the ten years in which we were operating the underwater laboratory *Helgoland* and we only used decompression with compressed air. And during the time we were under water the saturation depths between 8 msw and in America about 38 msw depth, we always used a mixture of nitrogen and oxygen where the oxygen minimal level was 0.25 atm and at a maximum level of 0.35 atm. One reason was to reduce the danger of fire, the second was to reduce long term oxygen effects on the lungs. And we never had a fire in the underwater laboratory. What we did have sometimes were some fuses burning and some insulated cables started smoldering a bit. But we had fire extinguishing systems and we had the possibility in case a fire would break out to evacuate the people and to flood the underwater laboratory with nitrogen. We had a nitrogen supply there to counteract possible burning. But we never had to touch it in 10 years. And before the tables were used for saturation in the underwater habitat they were all tested for at the DFVLR using a chamber. So we have sat tables, we have many here and we use them in Germany and they have been modified over the years. We had partial saturation tables up to about 50 hours in compressed air/nitrogen and after that full time saturation tables.

Sterk: May I comment? There is one thing only and that is in the Unterwasserlabor there was no downward excursion. The downward excursion is somewhat different.

Risberg: There are a number of tables available. And you know more tables than I do. What I wanted to find were tables that were credited, that were known, that had kind of an industry standard compared to what has been used in compressed air work. But there are very few tables that have reached a level of industry standards for regular air diving and saturation diving. I would like to be corrected if that is a wrong opinion.

Sterk: I don't think it is a wrong opinion. There is much more heliox saturation going on than air saturation or nitrox saturation, that's for sure. And, for me, I would choose heliox saturation for work beyond 30 msw or so. To have a habitat for scientific purposes on nitrox, that's perfect and it is comfortable. And I enjoyed it very much during the visit of the Unterwasserlabor.

Dr. Karl-Peter Faesecke: Just to go back from where we set out, let's discuss a given situation. Like you have reached 38, 39, 40 msw in a tunnel project, and you are expecting the necessity of deeper intervention. What mode should you choose?

Sterk: If you have reached 40 msw already, you are too late. I think you should start at the designing phase. Because it needs a lot of equipment adapted for trimix or saturation diving.

Le Péchon: A specialist situation.

Faesecke: That is understood. Saturation can't be changed once you are in the river.

Sterk: But even trimix, I think, should really be done in the designing phase and that's what I pointed out yesterday that engineers are always saying, "Oh, the machinery will do the work and there is no problem." Well, then we get into trouble because we have to solve the problem with limited equipment and limited possibilities because there is no space whatever. So then you are too late. You should do a risk analyses before.

Le Péchon: At least during the designing of the locks of the installation. You should ask for provisions that will allow you to do that. You don't need to install the mask or anything, but you must make the penetrators, and you must work out where you want to install the panels, what sort of analyzer you will want, and where you will put it. So you should have a provisional design so you won't be blocked. Then, according to the engineers of the machinery, they always believe that the machine is perfectly adapted to the ground they know. The problem is that they don't know the ground and the machine may be exhausted much earlier than expected. Then you have to make big repairs. If you go into that and you have made no provisions for extension of the capability of the expected compressed gas work, you are blocked. We had the same situation in Lyon; it was not to go in saturation. They had only one chamber, and they spent months just waiting on decompression. So provisions should be made to be ready to face the worst case scenario. It means if you are at a pressure where trimix may be needed for extended duration, you need two locks and you need the room to install the equipment.

Faesecke: But talking of worst case thinking, which may require at the deepest point of tunneling a three weeks' repair, constant shift work 24 hours per day; this would call for saturation, wouldn't it?

Le Péchon: Not necessarily. You can prepare by freezing the ground which is much cheaper than saturation. I'm sorry, it goes against us, we will all be out of work then.

Hamilton: Let me inject a comment that should be included at this point, the concept of the ascending excursion. I think I mentioned it yesterday. The *Aquarius* habitat is at a depth of 15 msw. They used to have a chamber on a barge above it. Aquanauts were decompressed in the habitat until they were at atmospheric pressure, and if they needed a treatment they could have it. The rule was, if you could catch them, put them in the chamber, don't let them go back down, but the divers knew the best thing to do was to go back down. That's another matter.

The point is that they got rid of that barge for cost purposes. There is only a life support buoy now. And I'm in the middle of doing procedures with them. They did this because the chamber is now a half hour away on the shore. It takes 30 minutes by fast boat, worst case.

They have what they call "gazebos", little houses, outside **Aquarius** and if they have to evacuate the habitat they get in those, call the boat, and the boat comes to fetch them. So they need a procedure to get to the surface, get in the boat, go to shore, and go back under pressure in the chamber. We are looking at the little bit of data that we have; there is not much. The US Navy has done spent a number of experiments. We did some trials in the NOAA OPS project to see how long we can excurse to a lower pressure and recompress without a problem. The requirement there was for 30 minutes. For the normal saturation situation at 47 fsw it takes 20 minutes of oxygen breathing. When they have made an excursion it may take a lot more. But it can be done. It would be a very unusual circumstance if they need to evacuate immediately after making a long or deep excursion. So for the most part there are procedures for a reasonable amount of oxygen breathing. They can breathe pure oxygen at habitat pressure. If they were deeper, they would have to use a mix.

So this is an extremely useful method to cover unlikely contingencies, and makes it possible to afford the habitat. Sure, there is some risk involved. But it was a chance they decided to take. You can get somebody out of a tunnel with that kind of procedure. If you do the right planning you could do it without a lock. I would not want to move an injured person, somebody who already has a decompression problem, without a lock, but to get someone out of the zone where they have high pressure and into the treatment chamber, that can be done in much less than an half hour here, I think, can't it? That's a viable method, so don't forget the possibilities.

Risberg: I am in favor of trimix but it is not fully explored yet. I am very much in favor of the trimix. I think there is only one reason that points against it. And that is the fact that it is not fully explored. I think we should keep on examining those divers with venous gas embolism monitoring. Having said that, I think that's the future. You are the caisson guys, you know, what is the probability for getting into a problem that lasts for weeks. If the likelihood of that is high you should install a saturation chamber. Because then it will pay off. If that probability is small, it won't pay off statistically. So even if you have to lose in one caisson job, you will win in the others. And you will probably be better off using trimix.

Sterk: Two things. First, Bill, your idea of having these people breathe oxygen and then transferring them at normobaric pressure to a chamber, I wouldn't do that to my divers or my workers. I wouldn't dare to. Why should I, there has to be a transfer capsule, also for the wounded personnel, so the transfer capsule is there, period. And we would use that all the time. It is different for a habitat out in the water for, let's say, scientific purposes. But these are working circumstances. And there is no way that in my country that the inspector of labor would agree to that.

The second thing concerns installing a heliox saturation chamber. I agree with what Jean-Claude said, it is very important to make provisions so that if it is needed you can put it on. You have your gas lines, your connectors and whatever. So you are ready to do it. But to put the chamber there, including the personnel to run it because that's the most expensive, wouldn't be wise. But you just make your technical preparations so you can do it if necessary.

And the last thing is that you can't, I think for the coming decade, rely on only experience in the past because I am sure we are going underground deeper and longer so we will go beyond our technical experience where we will try new techniques and mishaps will occur. Engineers can't foresee everything, and we should be aware of that. I've seen it too many times. For instance, in the Eastern Schelde I showed you, and on other projects as well. So let's get talking to the engineers in the designing phase. And show them what can happen. And what can be done from the human side. And then try to convince them, which is hard to do, I know, convince them to use that in their design. They can do it.

Le Péchon: I just want to show you a piece of equipment that is on this machine which has not been described during the presentation. It is a coring system, to evaluate the ground in advance. You stop the machine, you have means to core and to take samples of the ground. This is very practical for injection. So if you get stuck, here, with heavy work to do on the mill, even with this machine, you have means to cope with it. Without going to heavy repair work. Because you can use that to inject grout and replace the water which is in the ground with concrete. It will take time to make the holes all around, it will take time to inject, it will take time to wait for these to harden, but then you can open the door. So going always with hyperbaric solutions is only one way to do things. The cost, the training, the mechanical installation, everything climbs up to where it won't be acceptable any more. Then you have to change the picture and go into the ground and reduce the pressure so you can enter at atmospheric pressure. This is what was done during the Trans Channel program. And it has been done several times and this is much cheaper than preparing a saturation with the people, the tools, the training, and you are ready to do it. So the solution to take care of a problem in a tunneling machine is not necessarily going under pressure. It is a balance in economics and time and everything.

FINAL DISCUSSION

Dr. Karl-Peter Faesecke: The session is not yet over, gentlemen. You showed us a way going to nitrogen injection and icing the whole thing up, but not by tomorrow.

I will stir up another field of controversy which goes back to the title of the session: The limits of compressed air work. Where are they? Eight years ago we worked at 39 msw in Kiel with good success: No DCS cases. The new German regulations stepped back 3 msw to 36 where we are stuck now. I want to raise a question I discussed yesterday with Jean-Claude on the way to this meeting. We are all aware that there are different decompression tables for divers in compressed air work. Divers normally work shorter or decompress longer at an equivalent depth or given time. So we have diving tables that go beyond 36 msw. What happens if we use diving tables, in-water tables, in air? Shouldn't that enhance safety considerably? Because all the effects of immersion and all the additional physiological stress is not occurring. Can we just go ahead and use oxygen decompression tables from diving just in air? We just replace the medium water by the medium air. It's a question.

Dr. Wouter Sterk: On the contrary!

Mr. Jean-Claude Le Péchon: Just the opposite!

Sterk: The opposite, yes!

Dr. R.W. Bill Hamilton: You are not correct in saying that the physiological stress is worse in diving. The immersion factor does prejudice the decompression. You absorb more gas when you are immersed. But the work level is much higher in a tunnel than in most diving. If you work harder on a dive, you have to use a different table. The table doesn't work for hard work. So that aspect of it is one of the reasons why you have to have a little more concern.

If you look at it like in the Kindwall comparisons, what you have with the archaic tables. A diving table is a lot longer in decompression then a tunneling table. The reason tunneling tables work at all is because workers get acclimated, and decompression sickness doesn't get reported so they don't have to stop to treat it. And they compensate later for bone necrosis.

Sterk: Well, yes, apart from the hard work in various caissons. Also, the temperature is high, the humidity is high, it all adds to extra stress and extra uptake. And then during the decompression depending on the system, it is much cooler, so the wash out of nitrogen is going down, they are resting at that time. And we have seen is that in compressed air work if you use diving tables, which has been done also in Holland, you have a lot of decompression sickness. We saw a book about the Ij Tunnel in Holland of Dr. Meesters in 1967, and we had a lot of problems and a lot of bone necrosis there. And then they were using the Royal Navy Air Tables 11. Don't do that.

Hamilton: Those air tables weren't very good; they didn't use oxygen.

Le Péchon: In 1974 we had two groups of people working on different projects to make official tables. One was the group with Dr. Keller. He was working on compressed air tables. And at the same time there was Comex working on diving tables. They issued the tables independently. The compressed air tables were much longer. And we know they were not good enough as we had to change them in 1990. The tables which are there were discussed already. The tables for compressed air are calculated on the same algorithm as the diving tables but the [staging??] factor is reduced by 25% for decompressed air. And as we have the same duration of exposure in both I can put the figure on the board and you will see the difference.

Faesecke: But your book allows longer working time in diving than in compressed air.

Le Péchon: Yes. So I take a significant pressure, 4.2 bar or 42 msw compressed air diving. And we take one out. Sixty minutes; in that case oxygen starts at 9 msw and here oxygen starts at 12 msw. So this will be shorter, for this reason, but you will see that the difference in total time is very different. So for 60 minutes the first stop here is 15 msw and total decompression time is 70 minutes plus a few seconds. And if we go to the compressed air table for the same exposure, one hour, the first stop is at 18 msw and the total decompression time is 120 minutes. So there is a factor that reduces that time. But is not very significant since the stop in that range is about 15 minutes. So even if you go on oxygen or not it will change a few minutes. So there is a very significant decrease.

Faesecke: What about two hours working time? You can't do it on the air-table.

Le Péchon: I have the emergency table. The so called extra table. Which is on oxygen so it is for 90 minutes. The first stop then is at 18 msw, same thing. And the total time of decompression is 230 minutes. And here we have 90 minutes also, 42 msw, and here the time of decompression .... So there is half an hour bottom time difference. It means this one is shifted to the next exposure. So I don't want to say this is a Bible, this is what we have been able to produce. But this has not been used much. Only nuclear plants. It means about 100 times all together. That's all, so we have no significant experience on that.

Faesecke: But with diving we have decompression in water. And with diving in a tunnel we have dry decompression.

Le Péchon: This is dry decompression. Because at12 msw oxygen is not allowed in the water. So this is bell diving. It is air diving with a diving bell and transfer under pressure. Because oxygen in water at 12 msw is not permitted. So this is intended to be used with a diving bell and TUP on air. So this is dry decompression.

Sterk: It is the same conclusion only we don't go up to 42 msw for caisson work. You might go as deep as 35 msw. This is just diving tables and then you see that for 60 minutes at 42 msw we have about the same time of decompression, 67 minutes for diving but for compressed air work we don't do that. We can look at the 30 msw table I showed you before. For 3 bar, 30 msw, if you compare for instance the . . . If you look at the caisson table for lets say 90 minutes, it is 33 minutes on air/oxygen decompression. And when we go back to the diving tables for 60 minutes we have 43 minutes on diving time and on the caisson table it is about, 30 msw, 60 minutes, total deco time 43 minutes.

Le Péchon: For divers we have 31 minutes.

Sterk: O.K. then I am a little bit more conservative for the divers.

Le Péchon: But we have oxygen at 12 msw, so we have deeper stops on oxygen.

Sterk: No, No, No . . I started already before that.

Le Péchon: Your first stop is shallower than 12 msw. Our first stop is deeper. And then we go to caisson workers, 3 bar oxygen, 1 hour 52 minutes.

Sterk: At 60 minutes we have 48 msw.

Le Péchon: We have 52 msw.

Sterk: O.K. that's about the same.

Le Péchon: We are in the same range.

Sterk: I just wanted to check.

Le Péchon: But the difference is much longer decompression for caisson work than for divers.

Faesecke: In Germany, it is just the other way around.

Le Péchon: Okay, one of the tables might be dangerous. And I don't know which one.

Faesecke: But we use them everyday.

Le Péchon: Oh, but these tables may be too conservative. We don't know. Because we have no experience with the compressed air exposure on these tables except for nuclear plants in the range of more than 3 to 4 bars and a few tests and things like that, without work. So the tables which are here may be too conservative. But who will decide they are too conservative? We hope they don't make any problems.

Faesecke: Because another point is, if you go for one hour of work time and you have a job that requires like 30 man hours that means you have to compress and decompress 30 guys, 30 times. If you have two hours working time it would be 15 compressions and decompressions and that is a question of safety, also. Because every compression in itself is dangerous. This is regardless of whatever table you use. So of course we can be extremely conservative. Let's say we are not going to take anyone down longer than 60 minutes. But that would enhance the total amount of men being compressed and decompressed tremendously. So there must be some golden, some highway to travel, which is the right thing. Not too long exposure on air and not too short. Because too short means too many men at risk.

Sterk: But, therefore, the German regulations of limiting the exposures to such a limited time, 3 or 4 hours as a maximum per day.

Faesecke: That's what I am aiming at.

Hamilton: The concept of having a limit of an hour for diving has two reasons behind that. One is that most historic tables, most "legacy" tables, don't work very well for long exposures. And so the limiting the time like they did in the North sea for the surface decompression, limiting that to 30 minutes, solved a lot of problems. But, of course, it was a response to the needs of the company. But that is one thing, the shorter tables work better. Now that is because you don't have good algorithms. If you can improve the algorithms you can make the longer tables work better. The other factor is in both military and commercial diving there are almost always several divers standing there looking over the side of the ship waiting for their turn to go diving. So multiple dives were actually regarded as favorable. In most of those circumstances, certainly in the Navy. At least in our navy. It gave everybody their diving time. And it didn't matter that it wasn't the most efficient way. Would you agree with that? In a tunnel situation you are much better off to have one person work 4 hours than 4 people work one hour, in terms of the exposure.

Sterk: Right.

Le Péchon: Let us speak about oxygen decompression. When you can go to more than 1.9 bar you are limited to 6 hours under pressure. So in that range there is no decompression. You can stay there 6 hours and make multiple exposures or whatever. When you go more than this you start heading for the longest exposure, you start having some decompression. And you can see that except for a few minutes here you do not go further than 6 hours. But here there is some room for more working time. And today the tables are restricted to these maximum times. So at 3 bars you only have two hours decompression on oxygen. We are almost on the same values. But we have for each an extra table. Which is spare in case you do not close the door and you extend the time for any reason half an hour more. So we have the next one. And the next one in that range will extend over 6 hours. So it should remain safe. I have designed a very long extra table which we would use in case we would not close the door. But it is not the same family, it is just a spare emergency table. So we know already that the table at 3 and 3.3 bar with half an hour more, the next one works. And we have used it, we have 700 exposures on it. So we already know that the so called emergency table can be passed into the standard table provided we supply a means of coming out. Even if it is very long. Because it would not be a penalty for the operation, it will be a penalty for whoever has not been able to close the door. So it is no problem if it is one hour too long. So what is possible on this set of tables is first to use the next one. And the same algorithm can produce the tables, so these extra ones will have to be used very carefully of course. Because there is a point where the algorithm becomes long and high pressure will be no good anymore. We don't know where it is. So in this stage we are very careful. We have started using the next one already on operations, and it works, we know that. We know by a few hundred exposures, which is not much but with no cases of problems. So it can be extended, probably, but I think that staying at a maximum of 6 hours per shift under pressure is a reasonable value which provides acceptable times for the industry.

Faesecke: There is one problem with it. As soon as decompression time is longer than worktime you get stuck after the second shift. Because the first shift has not yet been decompressed when the second shift wants to enter the lock. So with this kind of setting you just cannot do that. So you have to have a ratio of one to one. Either two hours work, two hours decompression, or what have you.

Sterk: Or two chambers.

Faesecke: If you have two chambers you have the problem after the third shift.

Le Péchon: You need two chambers anyway.

Faesecke: Because they want to hand over the job to the next shift. So they have to be inside to take over, which takes about 5 to 10 minutes. But after three shifts you are really blocked up because the first have not yet completed decompression and the next are knocking on the door to get in. So that is a limitation.

And we had another limitation in our work at Kiel: I came to the conclusion that it is not feasible for the workers to spend more than two hours constantly on mask. Because after two hours on a mask they get weary, they look for means of getting rid of that thing, and they push it down or up. So to make decompression under oxygen more acceptable we said, "Let's limit decompression to two hours." And that is what you find in our regulations. We could work longer if we go for longer decompression but than we run into the problem of acceptance. And that is very important if somebody pushes his mask half way across the nose and he'll breathe only 60% of oxygen. He will run into trouble and so will we. So where is the way out? What are we going to do at 42 msw ?

Le Péchon: This is acceptability of the masks. When we did diving, for example on trimix or heliox, and decompressed people on mask on nitrox and on oxygen, we had to face that. And we decided that we should do the intermediate depths only on air. So that after the dive when they get in the chamber they have a rest period on air—it could be faster on nitrox. But we never accepted that they will be 6 hours on masks. So we go straight on air and they took oxygen at 12 msw on masks, with the breaks. So for deep diving we already faced that situation. But then with all your chamber full of people you have to wait, you can do nothing about that. And it is not an operational, it is a physiological problem. So of course you can reduce it slightly, but then you get into trouble more often.

Sterk: But, well then, at that depth use trimix. That is a solution; that will shorten your decompression time. And you can have some longer exposures.

Faesecke: Let me put out one more point. I was wondering why Dr. Nashimoto turned to using trimix at 30 msw already?

Sterk: I have shown you on the slide that instead of 100 minutes of decompression, on trimix you have 60 minutes of decompression.

Faesecke: I realized when I saw your video that what you consider work in a compressed environment is something totally different from what the old sand hogs have done for decades. Your guys who go in there today on their umbilical with trimix, they have to complete very distinct jobs like working on electronic devices and checking out modules and things like that. We have no experience with that. But at 30 msw of course there may be nitrogen impairment to judgement or to fine motor skills that requires the use of trimix at 30 msw already. And maybe if we come to jobs like that we just exchange some electronic devices or so. Our divers may realize they can't handle the job properly because it is the nitrogen; we haven't yet had that experience, but we should discuss that at least when we arrive at 40 or 42 msw. You may run into trouble having to do some delicate job, and the first group may come out and not have succeeded in doing it, even though they were trained for it. And they would hardly blame it on the nitrogen, because it takes some, well, courage to give in that you're susceptible to nitrogen and you cannot handle that job. It requires a certain amount of self criticism which is not very widespread with this kind of worker. So that is a point we will have to consider now that we are working in this area. We have air supply for divers up front. You have seen the umbilicals and the locks and so forth. So we could switch to trimix, we have the facilities. It's not that big a problem. My question again, the limit of compressed air work. Where do we switch from air to trimix. You say 30 msw because of the delicate work.

Sterk: It depends on the job; that's what we said.

Faesecke: For the delicacy of the job. If you require your full cerebral function you probably will not be able to do that on nitrogen on 33, 35, 36 msw. Do you agree with that?

Sterk: Yes. But these are only guidelines, as we said before, and you have to look at the particular job and the crew you are dealing with, and then you have to make your decision. In Nagoya for a large part it was engineers, not just caisson workers. Highly skilled engineers, themselves not so much experienced with going under pressure regularly, so a different type of people.

Faesecke: And that brings me to one point of this morning where I had asked for the importance of adaptation or acclimatization. It's not only about decompression sickness but also about this narcotic nitrogen effect. If we go down only every three weeks all these adaptations are gone and you have to start anew. So should we run acclimatization trials? When they are off work, should we put them in a chamber every day just to maintain the adaptation?

Sterk: Putting them in a chamber everyday adds to your likelihood of DCS.

Faesecke: I remember back in the early eighties when a British pioneer diving unit in Germany did recovery of ammunition from 55 msw in a local lake. And when there was bad weather and they couldn't dive, they came to our Navy chamber in Kiel to maintain their acclimatization. And they made their run at 55 msw for one hour including decompression in the dry chamber every day when they couldn't dive outside.

Sterk: Were these navy divers?

Faesecke: No, army divers.

Sterk: Yes, well, they get paid by the minute.

Faesecke: They told us we need the acclimatization and we have to receive our nitrogen dose every day.

Le Péchon: If they need that nitrogen dose everyday they're too wasted. They want it. That is one thing. They should have used trimix to dive and this would be finished.

Faesecke: They could have used laughing gas if they go for budgetting.

Hamilton: Also remember that Ichiro Nashimoto was trying to establish a precedent and introduce the gas a little bit earlier than necessary in order to get people used to thinking about it.

Sterk: There was also another reason. In Japan the caisson tables are in the law and, as you have shown us, they are not too good. The percentage of cases of DCI that needed treatment, so that must be serious cases, was up to 8% or higher. The only possible way to circumvent that was to use a new method in which you could use a new technique and new tables. And then the company could also show "Look, we didn't have any DCI." Which was not completely true but, o.k., no DCI that needed to be treated. So it depends on the situation also. Right now the economic situation in Japan postpones a lot of caisson projects.

Another point is that obviously it is cheaper to give about ten percent of your workers serious decompression illness than to use the new techniques, and then it depends on your attitude. I wouldn't like this situation here. When the tables are old fashioned, as we had in Holland, you should change them to get your DCI as low as possible. But then the question rises which percentage of decompression illness do you think is acceptable. And that is a crucial question which nobody, well nearly nobody, answers—not the government, not the people around it. You heard Dick Vann raise that question in our workshop in 1990. But the answers differ greatly. Some people accept a 5% bends incidence rate, others 2%, some zero, which should finish all high pressure work. Others 1%, well, you name it. But maybe you can give me an answer? There has to be an answer from the responsible people what we find acceptable.

Faesecke: Well, I once came down with 0.5%, that is one in every 200 exposures.

Sterk: Per schedule! Not over the entire range! I mean you have to look per schedule, of course. If you are starting at 0.9. you will have 0% and than when you end up at 40 msw you may have 10% and when you average you will have your 0.5%. and that is acceptable. I don't think so, you should look per schedule.

Mr. Hans Berkhof: I am a little bit surprised that we are talking about accepting decompression sickness. I thought we passed that point already. I know in the beginning when I started diving that it was normal that British divers always said, "When I go to the job there is a 10 to 15% chance of a diving incident or an accident and treatments." I am a little bit surprised because you do everything to avoid that. So starting to discuss before you start the job is so important. So that everybody is on one line. The thing that I am missing here is that we are talking about an ideal situation, that we don't have to go into the bentonite. If we have to go into the bentonite, it is much different. Is there any experience with this?

Sterk: This is, I think, a different question. With the first question you have to answer, "What percentage of bends do you think is acceptable." From the divers side, from the responsible people's side—responsible for the safety, for the health of the workers—if you say zero, then all diving work stops. If you say 0.1% then your decompression time will be 5, 10 times as long or something like that. It is tremendous.

Hamilton: Let me address this particular question. Yours is important but different. I found myself between the union and the diving companies in 1976 when the OSHA was trying to put together a standard for diving in the U.S. That was provoked by the union. The union would not accept even a tenth of a percent because that means you are approving decompression sickness. "The government approves decompression sickness." They would not accept that. So we did not issue a percentage of decompression sickness and incidence rate. We said all decompression sickness needs to be investigated. The employer needs to do everything possible to reduce the incidence rate. In reality the divers also knew that they were not going to get completely rid of decompression sickness or else they would get rid of their jobs. So the compromise was simply to avoid a target incidence.

However, I think the question is well taken here. Not necessarily that we need to make that decision. But rather that in every case you do want to have some idea of how disruptive it is and how costly it is to prevent. You certainly are going to have to make a trade off somewhere.

Sterk: And then the voice of the divers is very important on that.

Berkhof: I mean if you get a bends when you are working hard, of course, that can happen. But I think you have to move away from the idea that you accept bends because you are using a particular table.

Faesecke: Let me point out the approach that we have here on this construction site. When we started talking about diving safety, my approach was, of course: Zero cases. Because from my Kiel experience I was convinced that the tables are reliable, they are good. We could then trace back every single case of decompression sickness to one or the other small or big problem during the exposure. Somebody had hit his ankle on the door while walking in, so he got bent there. Somebody had sat on a cold piece of machinery, he got bends in his hips. The other had stood in cold water, and things like that. So we set out avoiding all these little problems and thereby reached a zero rate of deco-incidence for almost a year.

But we pretty soon found out that this is not feasible for all projects because you cannot have someone observe a caisson worker or diver all the time. They do make mistakes. They fall asleep in the chamber. The mask moves away. They sit in some distorted way. My personal conviction is that if you strictly obey the rules, observe every single item, are careful with what you do and how you do it, we could reach close to zero. I am not talking of acceptance. It is like a car accident. All of you are going in your cars today to, lets say, Holland. You are all aware that car accidents happen. You sit in your car and think, "Not me, I take care." If you take that attitude into diving and compressed air work you had better get out. You can never prevent someone else from the other lane running into you. And these things happen in diving and compressed air work also. But it is our job to make sure that these external factors, like the car, are O.K., that the road is free, the diver is sober, and all these things that you thought of. We have to influence these fringe factors. And that is our main job. We cannot fiddle with the tables everyday but we can make sure that the surrounding factors are optimal. And that's about the best we can do for divers' safety.

Sterk: But there is a particular point about diving tables. They are made for the average man. I've never met an average man. So there will be just a statistical variation. There will be people very susceptible and as you mentioned yesterday our ideal would be to have personal decompression tables. Individual decompression tables.

Faesecke: In a lock this is not possible. A diver can be brought up like that but not if you have five men in a lock. But it remains my ideal: Work with zero incident-rate.

Le Péchon: May I comment on this zero incidents. Statistically you cannot reach zero incidents. But what you may achieve is zero damage. It means that a certain number in the range of 45 percent of decompression cases are not acceptable, but they will happen. So you will have to be ready to take care of these cases so there won't be any damage. And what the divers are interested in is probably not to have small things, but to have these things taken care of properly so that there are no afterward consequences. When you take your car, there are emergency services which can take care so that you have a minimum damage. So in another type of coverage, we should organize the exposures and the tables to reduce the cases to the lowest possible. Which is probably in the range of much less than one percent. That is for sure. But in those small cases which are left, for various technical reasons, personal reasons, people being tired, having gone diving during the weekend, and all of these things. You need to cover the problem to reach no damage. And that is where we need the doctors to help the engineers to reach zero damage. The engineer can probably manage to get a very small level of decompression cases. But for the small number which are left we need the doctors. Even if I say we don't need doctors on site we need them to reach zero damage.

Faesecke: But the most important single factor in diver safety is still the diver himself.

Le Péchon: It is part of the game. So the training of people going under pressure is a very specialized training and it needs to be done very carefully.

Dr. Anthony Low: We have not discussed what the ideal decompression situation is in which a table works perfectly. What should the ambient temperature be in a decompression chamber? How should the seating capacity be? When I saw the slides yesterday with people cramped in small decompression chambers, I said, " Jesus, something probably will happen." We see wonderful tables but we do not hear what is the best ambient temperature for decompression. What is the best body temperature of the diver or caisson worker when decompressing? What is the best position he should sit in? These things are constructed in such a way that people sit like this or like this. I know from years with the underwater laboratory saturation decompression. I could guarantee you that somebody sitting reading a book with bent knees, when we leave one step and go to another, will complain in the next step that "I have pain in the knees." Now nobody asks questions about people sitting in a decompression chamber where men usually wear belts for instance, not braces like in the old days. Do you have certain segmental blood circulation disturbances during the decompression phase through the clothing that the person has on?

Hamilton: You want to be immersed in warm water like where you're born, breathing oxygen. But all of this stuff is a trade off. All engineering is a trade off. This is the same thing. But really you would be much better off with no pressure points but totally floating.

Low: But another question that comes to mind, since we are in the international community here, is that we have certain sort of differences in the medical field between black people, Caucasian white people, and say, Chinese, in medical aspects to a certain extent. Are there any sort of racial differences between the susceptibility to decompression sickness say with black people versus white people? I am not quite sure. I am in nautical medicine and we have a problem of small Philippine crew members on ships, multiracial ships. Now they issued individual survival equipment and there was a big complaint when the captain gave them the standardized size exposure suits. They completely disappear in them. The suits are not manufactured for their size.

Now you would certainly have people say that Filipinos diving with a very small body height and mass might also need a different set of decompression tables than those constructed in the West. I just wanted to raise the question.

Hamilton: I would like to reject that question if you don't mind because we can loose a lot of time with irrelevant things. I am serious. We shouldn't really try to answer that here. These are good questions. Each of us who is involved in this thinks of them. Like Walter said you plan and the planning includes consideration of being comfortable during decompression. But for us to get to details on that at this point is not productive.

Le Péchon: Can I answer the question of the ergonomy of the locks? This is the revision number 15 of the famous tunneling machine airlock safety requirement project of the European norm. And why are there 15 revisions is mostly to define the size of the locks. The seatings, the size, the cover, and the temperature, these 15 points mean 15 meetings because there is one revision at each meeting. There have been 15 meetings to find out the height, the minimum height, how to measure it, where if it is round, if it is not round, if it is sloped, because you have locks which have very funny sizes. Because they are not made when placing the machine. They use the machine to make the lock. So the lock has a very strange shape.

So there might be 1.50 m, which is the minimum height, in one place. But it may not be in another. There have been a huge number of meetings just to find something acceptable by everybody in terms of size, in terms of volumes, in terms of temperature, and it is normally finished unless somebody comes up and says "Oh the seat, there are small people, big people." So we went to the European norms for Ergonomics so that we could have an agreement coming from something else.

The size of the opening doors has been discussed extensively. Because of the stretchers, the dimension length and the door moving has been discussed extensively whether it was necessary that during the decompression the patient should be horizontal or could be placed like that. It depends on the duration of the decompression. So it has been quite a long discussion. And if you have the opportunity to go through that and you are not satisfied with the dimension, be careful.

Hamilton: Let me just throw out a conceptual way of doing this and we'll start with that as something to talk around.

Imagine now you are going to design a tunnel project and you are required to pass this group to get this group's approval. You are not going to get agreement—you can see that. There are going to be differences of opinion all along the way. But what would be very valuable and, I would very much enjoy this if I were designing a tunnel project, would be to be able to put it on the table here and find out what I have forgotten. To find out where I have made wrong assumptions. Because this group has a lot of points of view and a lot of experience. And we could be a lot of help in avoiding some of the pitfalls. For most of the organizations, getting to those pitfalls is not so great. As we do with aviation or whatever, as time passes we learn what works and what doesn't work.

But why not have a volunteer organization, or a sponsorship for it, so that people can afford to participate. You are not going to be quite so lucky as to have all these people come together to volunteer, to give their time freely, to assess somebody else's particular plan. But you could pick a half dozen experts with diverse viewpoints or experience in diverse aspects of the problem and arrange some kind of economic mechanism so that they can be paid for these meetings. Make it a voluntary opportunity for people planning projects in the next three to 5 years to present their concept and what they are planning to do, the problems that they have, the cross section and so forth, to a group of this sort. Don't get the group to do the planning. Get the group to vet the planning that has been done by the organization itself. And that includes medical and engineering and underwater work and whatever, the whole picture. I think it would be something that people would be probably be willing to do. And it might even be made such that the contracter or the consortium or government that is doing the work could actually pay this group so that people could get their daily consulting fees spending a day chewing on such a project.

Faesecke: Let me just explain one more time what the idea was behind it. I've been in the UHMS and EUBS now for over 20 years. I now observe that they, due to the big interest and the big money behind it, drift towards HBO_2 much more than diving if you look at the conference programs. There is very little diving left and hardly any compressed air work. Of course, there is only a small community interested in this field, but nevertheless, from an occupational point of view, from what we originally set out from, it should still be the core of interest of the society, the nucleus.

But we don't have anything like a committee on compressed air work, for instance, or deep tunneling, or whatever, where one could turn to. And that is what I want to instill into you to discuss.

Firstly, is there a neccessity and is there a way to handle it? Who is going to do it? It will not be me of course. But give me your ideas about that. For instance, a lot of committees are meeting in Seattle next month. It is three weeks from now. Why couldn't there be an afternoon on compressed air work? Well, how will we go on with deep tunnelling? Questions like that.

Also our German diving medical society is purely, well nearly, it is 90% HBO_2 by now. Even their little magazine is dealing almost entirely with HBO_2, how to extract the most money out of oxygen. And this annoys me really. I mean, if you are in occupational medicine and want to put people to work and get them safely back, money is not your main interest.

These two days have shown me that we have a lot of problems to deal with. We have a lot of agreements to reach.

And to go back to my main point, men are the same more or less and there shouldn't be that big a difference in susceptibility to oxygen or nitrogen or whatever. And we are coming together in all sorts of areas, we will have a European driving license by next year which will all look the same. So why don't we get European tables?

Le Péchon: Or at least a European certificate to start with.

Sterk: Well, I wouldn't point at the tables. Once again, tables should be changed every one or two years or as needed.

Hamilton: Tables should be project specific, absolutely. You have a good point there. An all purpose book that covers everything, we are sort of impressed by that. But for a particular project you really need to plan the whole thing as a unit. You said that yourself.

Le Péchon: Yes, yes, I agree.

Sterk: So that is an agreement. No European tables. But for other things we can give guidelines as I said, when do you, what would you accept as a limit for compressed air work. We could talk about that. Well, there is a range, it is not a rule, not a law, but it is the point where you should consider using other techniques.

Faesecke: One other point that I feel strongly about is what is helpful when you deal with authorities. I have been the authority myself for a couple of years, and now I am sitting on the other side of the table. When you deal with authorities who mostly are not very knowledgeable on these topics, it is much easier to convince them when you can say "Ah, this is so and so, Doctor so and so, Professor so and so." We have all sat on this topic and we all agreed, for instance, that from 38 msw you should start using trimix, and things like that. Also, with the construction companies and so forth, they like to take it from experts. It would be very helpful, because when you sit on the side of the enterprise and deal with the authorities, the authorities tend to think you get paid by the company and that is why you tell things that are in favor of the company. Which is, of course, not true.

Sterk: But it is also not true that you tell them it is so and so. That's what doctors have done for centuries. And until recently most patients believed it.

But I think that it is more honest to say, "Well this is the range and I wouldn't go beyond it with the present state of the art." But somewhere in between we should choose and you should get advice from several people or so. But to give strict rules, well, in Holland it would not work. As soon as there is a strict rule, people go over it. When we have a speed limit of 80 kilometers, we drive faster.

Faesecke: Yes, that is typical Dutch, I know that, I am half Dutch myself.

Le Péchon: And on the Mediterranean side it is worse.

Berkhof: Before we start an offshore job, everybody talks with each other about all the safety factors. People will study what kind of tables and what kind of hardware will we use. Before we start a construction job, everybody who is involved should sit around the table and do a risk analysis. For instance, there is nobody from the building company here, there is nobody from the factory here. I think it is ridiculous because this is the place where they can hear something. That is my personal opinion.

Faesecke: We invited them . . .

Sterk: At least there are people from diving companies here and that is already something. But really we should talk also with the engineers. Like we did in Oxford but on a bigger scale, better discussions and understanding of each other's points of view.

Hamilton: We didn't have the chance there to chew on these things the way we are doing it here.

Sterk: But I think that would be very valuable for the near future and also for the coming decades that there would be a group of, lets say, some occupational hyperbaric medicine doctors, caisson doctors, physiologists, what you call them doesn't matter, and some people from out in the field, and the engineers that design all this stuff, and make that a group to exchange ideas so engineers are finally aware of the limits of human intervention.

I think it would be very difficult to do but we can try at least.

Faesecke: All right, thank you very much, Doctor Sterk.

I take a second try, a closing remark now. And just to make it very short I am not taking anything away from you. From my point of view all speakers performed exactly up to my expectations. You delivered exactly what I had expected and hoped for. Thank you very much for that. I am exhausted but happy. But it was worth all the effort.

I promise that we will have a second workshop by fall next year as soon as we finish this job. And we will relate our own experiences along with other tunnel doctors who will be there, especially from Denmark.

So this should start a tradition, going back to Arthur Bornstein in Hamburg. And I thank you all very much for coming and spending these very precious weekend days, because it would have been a long weekend I know, with us here in this container village. I am very grateful that you all came. And you really made it very worthwhile.

And it will be a help to us also in our coming fights with government agencies, engineers, with household people, people who sit on the money, and so forth. From time to time you need a slap on the back from a fellow colleague to carry on the burden, it is not always that easy and we don't get that much of a reward.

When it is all finished, it is all blamed on the engineers when it comes out nice, and where it goes wrong they blame the doctors. We took this walk through the old Elbe-tunnel last night and they have the heads of all the construction engineers and the politicians and everyone on display, but the doctors are not represented nor the three men who lost their lives due to decompression sickness. But that's the way it goes. I think we get our satisfaction from the feeling that we do our best and we get the support from the divers, who are really the ones we are working for, not only working with, and I think that should do.

It is the later generations who raise somebody to what he really deserves like Arthur Bornstein. Thank you very much again and I truly hope to see you all again next year.

Maybe also in the meantime, if you are interested to watch our progress when we are going into deeper areas you are always welcome. No problem. But next time you have to travel on your own. Thank you very much and it is up to you for some closing remarks, for whoever feels the neccessity.

Sterk: Just one minute. I think somebody should say it: You have done a tremendous job in organizing this workshop in such a short time. It must be an enormous amount of work and I can imagine your are exhausted, so I give you the praise you deserve and which you want some time. I was very impressed by what you did.

Faesecke: Thank you, I wanted to impress you!

Le Péchon: You have been successful!

Hamilton: DAN concerns itself with recreational diving in the US. Several years ago a new procedure was brought out called the RDP as a mechanism calculating repetitive diving. They did some tests but they never got around writing a proper report. DAN really didn't know what to do with the results of this thing. So they put together an advisory committee. And that advisory committee met several times about that one project.

It was structured as if it was going to deal with others as they came along, but to tell the truth nothing else has come along. But it, in fact, exists as a concept. So if a client, or a developer, or a manufacturer, or someone of that sort, has a new product and they want to get DAN to work it over, while it doesn't necessarily mean it is going to get an approval, at least they will be able to get DAN's assessment of it.

They can do that, they can invoke this workshop, but they would have to pay some expenses. I would imagine in that situation since it deals with recreational diving those people would donate their time if someone paid their expenses. Most people would probably not require a stipend.

But the point is, there could be an ad hoc committee in existence identified and advertised to the construction community. If you want this kind of assessment we can bring it to bear. You could say this is a product of this meeting. We have a group of experts that would be willing to assess a program, and who you get depends on the things that are being assessed.

Sterk: Yes, but that depends also on the law in a particular country. In our country we have occupational doctors which are organized as ARBO. And they are the persons that should do the risk analyses and whatever, and they have to do. By law, it is theirs. But they need to ask the experts so it wouldn't be a company.

Hamilton: It might be a government organization. A so called authority.

Sterk: Yes.

Dr. Ben van der Putten: The special health services of the ARBO are just free enterprises.

Sterk: Yes, but that's because the Dutch government has said that they profitized everything.

van der Putten: A contractor is required by law to do a risk evaluation.

Hamilton: Dr. Mader has sat very quietly and listened to all this. He is in Austria and they are facing a new metro in Vienna that goes under the Danube. Presently, they are having to revise their regulations because they can't do it under the existing regulations.

Your government, whatever organization, the ministry of labor, who ever, could very well say, "We should get these people to help us." You are at a turning point and you can make wrong decisions that cost you dearly. Mainly in terms of expense and possibly in terms of human suffering.

Dr. Clemens Mader: It is my intent when I go back to write a short report on this meeting, on this workshop, and outline a few important facts of prospective planning of such a big construction site. And to include specialists that are willing to bring in their experience and their knowledge, especially pertaining to a special construction site with special demands.

That's what I will take along with me from these two days. And I am glad that I could come here, thank you, and I am glad I met you and this will enrich our compressed air work. I think that it is very difficult to find somebody who is an expert on this. There is hardly any literature published. It is very difficult to find literature. Or even to find people on the Internet who could give you any definitive information. Professor Sterk was called by me, one or two times. And he gave me some valuable information, but I am glad that I met you from France, Jean-Claude, and I am glad that I met you, Dr. Hamilton. So I think it could be a very fruitful cooperation within Europe and between Europe and the U.S. This workshop has been a very important instigation.

Faesecke: Well, it sounds good. That's what we wanted, thank you very much. So I now declare the bazaar closed. Thank you all very much again.

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