

SAFE DECOMPRESSION SCHEDULES
FOR CAISSON WORKERS

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16. Abstract (Limit 200 words)
A 3 year program designed to evaluate new decompression tables for compressed air workers is described. Development of tables from commercial diving data is reviewed, along with the general considerations and procedures used to compare these and OSHA tables using human subjects. Specific methods are described for whole body nitrogen washout studies and ultrasonic bubble detection experiments. The authors conclude that little difference exists between the decompression schedules given by these decompression tables and OSHA tables; however, the decompression tables are significantly better than the OSHA tables since they combine the use of oxygen and stage decompression which have synergistic effects in increasing nitrogen elimination during decompression. The schedules may be difficult to implement because of added equipment costs and the need to retain caisson crews. Appendices are included which present tables for oxygen and air, rules for the use of oxygen during decompression of compressed air tunnel workers, employee safety guidelines, inspection check lists for safety engineers and physicians, and a report and evaluation of the need for interim decompression schedules to replace OSHA schedules for tunnel workers.

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SAFE DECOMPRESSION SCHEDULES FOR CAISSON WORKERS

NATIONAL INSTITUTE OF OCCUPATIONAL SAFETY AND HEALTH
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FINAL REPORT

Introduction and Background

In 1971, the Washington State decompression tables for compressed tunnel workers were adopted as the federally enforced code for decompression of these workers. Previous experience in Seattle, San Francisco and Milwaukee, Wisconsin had not shown any incidence of aseptic necrosis in tunnel workers who decompressed on these tables exclusively. Thus, it was felt safe to adopt them for national use.

However, on a tunnel job in Milwaukee, Wisconsin which took place between 1971 and 1973, 40 men worked on a compressed air tunnel job at pressures which exceeded 36 psig. The OSHA code was used on this job having been adopted by the State of Wisconsin as early as 1970. In 1975, 3 men who had worked on this contract were discovered to have aseptic necrosis of the bone and on the basis of this, a NIOSH grant was secured for the x-ray follow-up examination of the men who had worked on the contract. Twenty-one of these men were located and x-rayed. Seven of these twenty-one ultimately were shown to be suffering from dysbaric osteonecrosis due to occupational exposure in compressed air.¹ As a result of this study, it became apparent that new decompression schedules were needed to replace the present OSHA enforced schedules which had created these lesions. In addition to dysbaric osteonecrosis, the federal schedules also produced an alarmingly high incidence of decompression sickness.

As a result of these findings, two workshops were convened by the Undersea Medical Society at the behest of NIOSH to determine the feasibility for developing interim decompression schedules to replace the present federal schedules which have been shown to be dangerous. A series of specifications were drawn up for these tables. The specifications were as follows: 1. A maximum decompression sickness rate of 5% with non-serious classification. 2. A maximum dysbaric osteonecrosis rate of 4% with shaft lesions only. 3. A minimum tunnel or caisson depth of 112 feet (50 psig).

The first meeting was held on July 23, 1979 and it was agreed that these tables should be developed. (Appendix XI)

Mr. Peter Edel (Sea-Space Research Company of Harvey, Louisiana) was entrusted with the task of producing computer generated new tables based on 15 years experience with successful and unsuccessful commercial dives as well as the Tektite dives and Navy experience.

Mr. Edel subsequently produced these new tables and a second workshop was convened by NIOSH at Undersea Medical Society headquarters to evaluate the new proposed interim decompression tables. (Appendix XII) On the basis of preliminary approval of these new tables, at least for testing, NIOSH issued the research grant which is addressed in this final report.

Starting February 1, 1980 and ending April 30, 1983, these tables were systematically tested in the laboratory on human subjects to determine their safety with regard to decompression sickness and aseptic necrosis of the bone.

Additionally, quantitative measurements were made of nitrogen whole body washout comparing the OSHA schedules and the new decompression schedules. If more nitrogen could be washed out of a subject after decompression on Schedule A versus Schedule B, Schedule A was considered less efficient.

A third aspect of this project was to determine whether or not ultrasonic tissue imaging could detect asymptomatic stationary bubbles in humans and whether or not they could be used to quantitatively assess the efficacy or safety of any given decompression schedule.

Two new schedules were ultimately developed, a set of air decompression tables and a set of decompression tables using intermittent oxygen breathing. It is strongly advised that the new oxygen decompression tables be adopted for commercial tunneling in the United States. These tables are now labeled the Edel-Kindwall Caisson tables (Oxygen). (Appendix I)

TABLE TESTING

The main thrust of this research project was to develop new decompression tables for compressed air workers which were safer than the currently enforced OSHA schedules. This involved the computer production of the new tables followed by their testing. Mr. Edel developed a set of tables called Autodec II which were equal to or longer than the current OSHA schedules and which had been based on previous commercial diving experience. Autodec II was used to analyze the current OSHA schedules for adequacy (in comparison to Autodec II) and OSHA tables were graded on a rating scale from A+ through i, A+ being more than adequate decompression with i being grossly inadequate. All of the exposures used in Milwaukee tunneling contracts were E or worse with the exception of the 7 hour exposure at 16 lbs. which was rated as C. The exposures in excess of 36 lbs. were rated G and H. It was on these latter exposures that aseptic necrosis to the bone was noted in 33% of the workmen surveyed.

Mr. Edel also developed a longer set of decompression schedules labeled Autodec III. Autodec III used commercial diving data from much longer schedules than the Autodec II version and based on this new information, Mr. Edel felt that Autodec III would be much safer. However, initial examination of the Autodec II and Autodec III schedules presented to the laboratory in November, 1980 showed that the Autodec III schedules using air for decompression were too long to be commercially usable. Therefore, even though there were questions about Autodec II table adequacy, it was decided to test

these tables with one or two dives at each pressure level from 14 lbs. to 50 lbs. to see if they produced any appreciable incidence of decompression sickness. The number of dives scheduled to test tables was purposely limited in order to conserve funds. At each pressure level, we tested the table which provided the maximum amount of time at depth which when combined with the total decompression time, fit within an 8 hour working day. From a practical standpoint, these are the only tables which will be used in normal field operation.

No decompression sickness was produced, spot checking the table, until we tested a table at 34 lbs. One of our subjects after spending 4 hours at 34 lbs. and decompressing in 3 hrs. 59 minutes, suffered chokes appearing three hours after the end of decompression. As chokes are serious symptoms, it was decided that this was a demonstration of the Autodec II tables' inadequacy at pressures of 34 lbs. or greater. Subsequently a second subject worked at 28 lbs. for 4 1/2 hours, decompressing in 2 hrs. and 42 minutes. He suffered severe pain in both knees and the right shoulder; symptoms first appearing approximately 1 1/2 hours post decompression. In both these instances of decompression sickness, the subjects were relieved promptly on recompression and treatment on the U.S. Navy Table 6.

A third subject was exposed to 26 lbs. psig for 5 hours on Autodec II and suffered delayed pain in his left knee. The same subject after spending 4 1/2 hours at 28 lbs. on Autodec II did not suffer knee pain but his partner experienced decompression sickness. These exposures occurred in September of 1981. When this subject was given a routine x-ray and bone scan on June 11, 1982, there was an area of increased activity seen in the left proximal tibia. The x-ray was negative however. Follow-up on this subject carried out on June 26, 1983 showed that the increased activity in the proximal left tibia first noted on June 11, 1982 was less intense than on the previous study. The remainder of the bone scan was unremarkable. Furthermore, the x-ray taken on June 28, 1983 was completely negative for bone lesions.

Thus, from the foregoing it was clear that the Autodec II tables were inadequate and too slow. It was clear from inspection of the Autodec III tables that an impasse was reached at a pressure of 30 psig with a working period of 3 1/2 hours. Decompression from this exposure required 3 hours 58 minutes, longer than the working time in the tunnel and additionally resulted in only a 7 1/2 hour working day. It is impossible to use a caisson schedule where the decompression time is longer than the working time because the decompression or manlock will be tied up decompressing the previous shift when it is time for the following shift to lock out. Thus, beyond 28 psig, Autodec III using air decompression, becomes physically unworkable as well as being economically not feasible. From a standpoint of economics, Autodec III would probably cease to be practical at pressures greater than 18 psig if air were breathed during decompression.

The logical conclusion was that if compressed air tunneling is to be carried out, the only feasible way to accomplish it is to provide oxygen breathing for the workers during actual decompression in the manlock. It was for

this reason that the oxygen variants of the Autodec. schedules were developed. The advantages of oxygen breathing are enormous. For example, if the worker were to work at 44 lbs. for 4 hours and decompress on air, Autodec III calls for a decompression time of 10 hours and 46 minutes. This of course is unacceptable for the reasons outlined above. However the same exposure requires only 3 hours 21 minutes decompression if oxygen is used. From the economic standpoint this is a slightly shorter decompression than required on the present OSHA tables for 4 hours work at 44 lbs., and also, decompression time is less than the actual shift time making it possible to use the same manlock for both incoming and outgoing shifts. However, at the extreme limit of the Autodec III oxygen table at 48 and 50 lbs., none of the decompression schedules is shorter than the exposure time even using oxygen. Thus, for practical use, compressed air tunneling will have to be limited to a maximum pressure of 46 psig from now on. From September 8th of 1982 until November 30, 1982, 22 dives were made using the Autodec III oxygen decompression schedules. These tests were conducted at 2 lb. increments from 12 lbs. to 46 lbs. Tables were tested with 2 different subjects at 24 lbs. and 28 lbs. and with 3 exposures at 44 lbs. No symptoms of decompression sickness were reported on any of the schedules with the exception of one subject who spent 5 hours at 34 psig. He reported pain in his left knee on walking but it was inconstant and this subject had also previously had trauma to that knee. Another subject working at 38 lbs. for 4 1/2 hours complained of skin itch and a feeling of warmth below both knees starting 60 minutes before decompression. He also complained of slight ankle pain on surfacing. This was not severe enough to warrant treatment as it did not persist and was classified as a niggle.

In each case, the table tested was the one which provided the maximum working time which when combined with decompression time, produced an 8 hour working day. While the patient was exposed at maximum pressure in each test dive, he walked on a treadmill at 3 mph on a three degree incline picking up a 5 lb. weight in each hand every tenth step and raising them over his head. Time spent on the treadmill was 10 minutes for each working period followed by 10 minutes rest after which the cycle was repeated until decompression commenced. It was therefore concluded that the Autodec III oxygen decompression tables are relatively safe at pressures up to 46 psig using exposures likely to be encountered in commercial compressed air tunnels. At least, during the testing of these tables, a serious case of decompression sickness did not result in any of our test subjects in the laboratory while carrying out working exposures designed to simulate conditions as they would be in the actual tunnel. Because of the prohibitive expense of doing hundreds of dives to develop a bends incidence or frequency using these tables, we cannot state what the bends incidence will be when these tables are used in the field. However, we have been able to rule out catastrophic inadequacy of the tables and if they were significantly worse than the OSHA schedules, or even as deficient at the present OSHA schedules, we would have expected to see more in the way of decompression sickness during their testing. Also, all our subjects were purposely unhabituated - rendering them much more susceptible to decompression sickness than habituated shift workers. Furthermore, follow-up examination of all of the subjects involved in these tests using x-rays and

bone scans taken 6 months after the conclusion of the last test, showed no new changes or pathology.

It was intended that the Autotec III oxygen schedules be used on a compressed air job in Cleveland, Ohio. However, OSHA dragged its feet concerning the granting of a variance from August 1982 until January 1983. By that time, the job in Cleveland had been completed and it was not possible to use the tables commercially. It is of note that the contractor had to spend \$400,000 in grouting costs to control water leakage because he was unable to raise the pressure higher without going to the use of oxygen.

Nitrogen Washout Studies

Starting in 1972, this laboratory developed a method for measuring the amount of whole body nitrogen that could be washed out of human subjects during or following decompression from a dive². It was felt that this method could be used to provide objective evidence of the superiority of one decompression schedule over another without having to rely on the appearance of overt symptoms.

Materials and Methods

The apparatus used for the whole body nitrogen washout studies included a mass spectrometer, a hyperbaric chamber and a closed circuit breathing system. The mass spectrometer (Scientific Research Instruments MS-8) was dedicated to 5 gases: nitrogen, helium, oxygen, carbon dioxide and argon. This instrument has been field modified to provide measurements as small as 100 parts per million (one 100th of 1%). The mass spectrometer was calibrated against known calibration gases equilibrated to chamber pressure immediately before taking a sample. Calibration gases were supplied by Mattheson Corporation of Joliet, Illinois and were traceable back to the National Bureau of Standards.

Hyperbaric Chamber

The hyperbaric chamber was an 8 foot by 20 foot double-lock steel chamber capable of 90 psig. The chamber was equipped with cooling coils and heating coils to maintain a comfortable temperature during the course of the research. All of the research apparatus except the mass spectrometer and calibration gas bottles was situated inside the inner lock of this chamber.

Closed Circuit Breathing System

The breathing system (Figure 1) could function in either the closed circuit or open circuit mode. The closed circuit system for nitrogen collection consisted of a 120 liter Collins spirometer filled with approximately 50 liters of oxygen (99.7% pure). This was connected in turn with a mouth piece, carbon dioxide absorber containing Baralyme and a supplementary oxygen

three. Two three-way valves in the system permitted opening a portion of the circuit for breathing oxygen at the beginning of the experiments while leaving the spirometer isolated from the subject. This made possible a lung rinse. When nitrogen collection was begun, the subject was switched to closed circuit with the spirometer. A rheostat attached to the spirometer support wheel and connected to a digital display provided data on the spirometer volume.

Procedure

Six volunteer subjects ranging in age from 26 to 59 participated in these experiments. They were either scuba divers, scuba instructors, former compressed air workers or subjects who had previously volunteered for hyperbaric studies in this laboratory. Some were smokers and some were not smokers as no attempt was made to provide "perfect" specimens as the tunnel working population is composed of a broad spectrum of physical types and differing physical condition. Chamber temperatures were maintained so that the subjects were subjectively comfortable. Each subject worked on a treadmill during his exposure to compressed air, walking up a 3% grade at a speed of 3 mph. Every tenth step he was instructed to raise a 5 pound weight held in each hand from a position at his side to above his head. The subject walked on the treadmill for a 10 minute period followed by a 10 minute resting period. This was to approximate a "moderate" work effort throughout exposure to compressed air in an effort to simulate the work effort of a tunnel laborer.

Tables Compared

Initially we compared the present OSHA decompression schedules with a schedule developed by Mr. Edel labeled Autodec II (see Graph I & II Appendix III). Autodec II was characterized by having stage decompression as opposed to continuous decompression avoiding long periods of time spent between one or two pounds and the surface. The shallowest stop on Autodec II was four pounds. The Autodec II schedule tested was equal in length to the present OSHA table. However, because of difficulties encountered with Autodec II (decompression sickness and bone scan activity in one subject) these tables were abandoned and Autodec III was substituted (see Graph III). Autodec III also was a stage decompression table using either air or oxygen. Because the air decompression table was so long, it would have proved to be impractical in commercial use. Therefore, we opted to use the oxygen version of the Autodec III schedule. Our final nitrogen washout studies were done comparing the OSHA table against the Autodec III oxygen schedule. The schedule used was an exposure at 24 lbs. for 4 hours followed by decompression on either the OSHA or the Autodec III oxygen schedule.

Procedure

Each subject was compressed to 24 lbs. in approximately 3 to 4 minutes for 4 hours while the subject worked on the treadmill. After 4 hours the subject was decompressed according to either the Autodec III or OSHA tables with a surface

interval of 5 minutes. At this point the subject was recompressed to 14 psig and put on open circuit oxygen to accomplish a 2 minute lung rinse. Then each subject was put on closed circuit and readings were taken at 3 minutes, 5 minutes and every 5 minutes thereafter for a total of ninety minutes. During the washout phase the nitrogen elimination was measured by a digital mass spectrometer previously described. It must be noted here that preliminary studies done with Autodec II failed to show significant differences from the OSHA table. Subjects were recompressed to 14 lbs. during washout to diminish any possible capillary blocking effect of nitrogen bubbles and enhance total nitrogen washout.

Analysis of Data

We obtained whole body nitrogen washout profiles for five subjects on both the OSHA and the Autodec II schedules. Then each subject's profile on the OSHA schedule and on the Autodec II schedule was compared. Since each subject had at least one profile from each table, we used The Statistical Model of Experiments Having Repeated Measures on the Same Elements* (ANOVA). (Fig. 12-17, Appendix XIII)

It was evident that there was no statistically significant difference in the use of Autodec II in comparison with the OSHA schedule. This was confirmed with a "p value" of 0.4540 overall. In addition, we noted that there was no statistical significance between subjects at the level of 0.8081. Therefore, we must assume that the use of Autodec II is not more efficacious in the elimination of nitrogen than the current OSHA table. However, it would appear that the use of the Autodec III oxygen schedule is superior to the OSHA schedule in denitrogenation with a "p value" of 0.0850.

*Winer, B.J., Statistical Principles in Experimental Design, 2nd ed., Mc Graw-Hill Company, 1971, Chapter 7.

ULTRASONIC BUBBLE DETECTION EXPERIMENTS

Introduction

The technique to detect stationary tissue bubbles during and following decompression using ultrasound tissue imaging was first conceived by MacKay³ in 1963 and later put into successful practice by MacKay and Rubissow.⁴ These studies were done for the most part in small animals decompressed from depths as great as 13 atmospheres. In this project, we hoped that we could demonstrate the formation of decompression bubbles before they produced symptoms in human beings. This would give us, in theory, another method for objectively comparing the old and new tables for efficiency without resorting to overt symptoms as our only guide.

Methods

After discussion with co-investigator Melton, a specialist in ultrasonics, the ADR ultrasonic tissue imager operating at a frequency of 5 MHz was selected. The ultrasonic scanner was connected to a strip chart recorder using a signal processor which had as its function to take the video signal as it was delivered to the CRT screen and integrate the changes in the image elements so that they could be displayed as a single line chart recording. Initially, it was not known whether the appearance of bubbles would lead to an increase in the number of image elements contained in scans of the selected tissues or whether there would be an increase in the strength of image elements contained in scans of the tissues. Depending on which hypothesis was true, a suitable integrator had to be built. Initially, the integrator was constructed to detect an increase in the number of image elements contained in the scan.

Transponder Placement

The placement of the scan head was the next problem to solve. Motion of the subjects which would displace the scan head even slightly during the course of an experiment could severely alter the readings. We did studies in vitro with chunks of meat which had been saturated at high atmospheric pressure and then decompressed with the scan head coupled to the surface of the meat using a water coupling. We felt that bubbles could be detected in non-viable meat. Therefore, we turned our attention to assessing various methods of placing the scan head on the human. The Oxford group (Daniels et al)⁵ had previously used the ADR machine strapping the scan head to the antero-

medial thigh but we found this method too unstable to generate reproducible data. We tried applying the transducer directly to the skin and then we also built a water-filled plastic standoff with a thin rubber diaphragm closing it where it rested on the skin to avoid possible blanking out of the electronics by bubbles appearing within the first centimeter.

Experiments were also carried out using a water bath coupling in which the arm was immersed but this proved too tiring to the subject even when a cast was applied to keep the arm steady. Bubbles in the water also produced artifact and we found that bubbles also appeared on the skin surface. The subscapular fat pad was unacceptable as respiratory movement produced artifact.

Finally, we analyzed the cases of decompression sickness in tunnel workers previously treated at this facility and discovered that the vast majority suffered symptoms in the lower limbs from the knees down. Therefore, we made individual bivalved fiberglass casts for each subject in which a window was cut over the gastrocnemius muscle. The probe, with water-filled standoff was applied to the skin through this window with a mineral oil coupling. This produced a steady baseline and was tolerable over long periods to the subject. The transducer was clamped to a steel post affixed directly to the cast adjacent to the window to avoid movement. Care was taken so that the skin contact pressure was low as we felt that excessive contact pressure might prevent bubble formation in the underlying tissues during decompression.

Integrator

After the positioning of the transducer seemed adequate, we still got mixed results and turned our attention once again to the integrator. Two new integrator designs were made for true integrating bubble counters. One design utilized integration followed by sample and hold and the other design incorporated a slowly relaxing integrator. The latter design worked better. The sample and hold devices were not capable of holding the integrated image elements of values with sufficient stability whereas the slowly relaxing integrator operated with the requisite stability (holding time of 1 microsecond, relaxing time of 5 seconds).

Even with the new instrument which should definitely have been able to detect bubbles, results were still mixed and ambiguous. In a critical experiment, one of our laboratory staff members volunteered to be decompressed after a four hour exposure at 16.3M (54 ft), directly to the surface. He was held on the surface for 13 minutes while careful recordings were made to detect bubble formation. There is no question that bubbles would be generated under these circumstances. After 13 minutes, the subject was recompressed to 18M (60 feet) and placed on oxygen. He suffered no overt symptoms and the safety of this experiment was based on previous work of one of the co-investigators.⁶

During the 13 minute surface interval, no bubbles were recorded using the 5 MHz ultrasound machine. Thus, it seemed that the hypothesis tested negative.

Frequency

At that time, we noted that the original work carried out by Mackay in 1963 used 7.5 MHz. When we had originally purchased the ADR 5 MHz scanner, we were told by the company that the 7.5 MHz scanner head would soon become available. However, after the equipment had been delivered the company cancelled plans to market a 7.5 MHz transducer. Therefore, after 8 months experimentation with the 5 MHz apparatus, we chose to go to a higher frequency of ultrasound so that backscatter for small bubbles in tissues could be increased above the level of backscatter due to mechanical discontinuities normally present in the tissues. Consequently, a 7.5 MHz transducer was borrowed from the Department of Radiology at this institution along with a pulse receiver from the Medical College of Wisconsin to test the hypothesis at 7.5 MHz. Ultrasound could be used to detect the presence of decompression bubbles in tissues in vitro. Several trial experiments, in vivo, were undertaken to test the use of 7.5 MHz but no bubbles could be detected using the new equipment including a new integrator. We then constructed a 4 cm. water-filled standoff to view the subcutaneous fat pad. Preliminary experiments indicated that bubbles were present so we decided to execute a third step to secure a new scanner capable of operating at higher frequencies. The Ocuscan YE model manufactured by Sonometrics was secured on rental and it was also tried. The Ocuscan scanner was equipped with a 15 MHz scanner head. However, after some preliminary experiments seemed to indicate subcutaneous bubbles over the gastrocnemius, further investigation showed these signals to be spurious. By July of 1982, we had concluded that ultrasonic tissue imaging of stationary bubbles was not possible in asymptomatic human beings at least using the equipment we had. At that time, we had concluded that if small bubbles were to be detected in muscle, the frequency had to be greater than approximately 16 MHz for bubbles of approximately 5 microns diameter. This calculation was consistent with our findings to that time with decompression bubbles in vitro.

The results of the above described experiment led to the hypothesis that small isolated bubbles in soft tissues (mostly muscle) do not scatter ultrasound with more intensity than does the surrounding soft tissue. This hypothesis was tested in vitro and in vivo for cardiac and for skeletal muscle, by measuring the average envelope of detected rt scatter, accounting for attenuation of intervening media, and normalized to the average "backscatter" from a 100% reflector (Miller). Also such measurements were made on isolated small bubbles (generated electrolytically using needle electrodes and pulsed power source) and normalized as shown. Bubble size was estimated from measured rising velocity in phosphate buffered saline (this velocity was measured as a change in ultrasonic pulse echo range per unit of elapsed time)

The measured average backscatter for muscle was approximately -50 db (normalized to a perfect reflector) whereas the measured average backscatter for isolated bubbles of 40-50 μm diameter was approximately -60 db. The above measurements were made using 5mltz operating frequency (nominal). From the measurements the average normalized backscatter from isolated bubbles of 2-5 μm diameter was estimated to be between -70 db and -80 db.

These results indicated to us that ultrasonic detection of small isolated bubbles in vivo within soft tissues cannot be readily perceived in B-scan images because of the inherent ultrasonic speckle. The basic difficulty that this raises is that the spatial pattern depicted in a B-scan is not congruent with the spatial pattern of fundamental acoustic properties of the object. Thus bubbles could not be seen on the CRT screen but they could be detected electronically. The detected rf envelope takes on a Rayleigh distribution for scatterers.

$$f(a) = \frac{a}{\sigma^2} \exp \left[-a^2 / (2 \sigma^2) \right], \quad (1)$$

where $f(a)$ is the amplitude density function, a is the amplitude of interest and σ is the rms value of the rf signal referred to the detector output. The average value for this backscatter is related to σ :

$$\mu = (\pi / 2)^{1/2} \sigma \quad (2)$$

where μ stands for the average value. When a few small bubbles are added in, σ changes value ever so slightly:

$$\sigma_T^2 = \sigma^2 + \sigma_b^2, \quad (3)$$

where the new rms value σ_T is related to the addition of bubbles with an rf rms value σ_b . Consequently,

$$f(a) = \frac{a}{\sigma_T^2} \exp \left[-a^2 / (2 \sigma_T^2) \right]. \quad (4)$$

Now by assuming we can measure the frequency at which the detected signal either exceeds or falls below a given value the measurements will follow one of two cumulative functions, F:

For $x < a$,

$$F(x) = 1 - \exp \left[-x^2 / (2 \sigma_T^2) \right]; \quad (5)$$

For $x > a$,

$$F(x) = \exp \left[-x^2 / 2 \sigma_T^2 \right]. \quad (6)$$

The question arises: at what values of x will these measurements have the greatest sensitivity to changes in σ_T or more specifically σ_b ? This question is answered by taking the derivative of the cumulative functions with respect to σ_b and finding values of x for the extrema. Consequently one finds that two conditions are defined: x approaching zero or x approaching

infinity. The latter condition is readily eliminated because instruments have amplitude bounds which leaves the first condition as the avenue for measurements. This condition can be utilized to structure measurements after Eq. (5) or Eq. (6). Again an approach using Eq. (6) is readily eliminated to avoid large values of measure encountered as x approaches zero. This process of elimination brings us to one approach, Eq. (5), for measurements of the presence of small isolated bubbles in soft tissue, whose backscatter is imbedded in the backscatter from the surrounding soft tissue.

The block diagram of the instrument used for measuring the frequency of occurrence as given by Eq. (5) for x very small is shown in Figure 2. The video taken from the scanner was amplified and fed to a comparator. Its output was high when the video exceeded the threshold-set; it was low when the video fell below the threshold-set. The following clocked AND gate provides the drive signal to the integrator which provides the measure of the cumulative probability that the video, x , is below threshold, a . The switching PAM filter removes the integrator Sampling - Reset artifacts. The threshold was set by first measuring the average value of video (at the comparator input) caused by backscatter from the calf-muscle. Now from previous measurements, the ratio of backscatter from small bubbles to backscatter from muscle, R , can be found using Eq. (2):

$$R = \frac{\mu_b}{\mu} \text{ (db)} = \frac{\sigma_b}{\sigma} \text{ (db)} \doteq -26\text{db} \quad (7)$$

Having measured μ referred to the comparator input one can directly solve for μ_b referred to the comparator input.

$$\mu_b \text{ (volts)} \doteq \frac{1}{20} \mu \text{ (volts)} \quad (8)$$

These values varied some from subject to subject even though the scanner gain was fixed. This value of μ_b was used to place the threshold-set so that the output on the strip chart recorder followed as closely as possible the same scales from experiment to experiment. This method of setting threshold allows simplification of Eq. (5):

$$F(\mu_b) \doteq 1 - \left[1 - \frac{\mu_b^2}{2\sigma_T^2} \right] \quad (9)$$

$$\doteq \frac{\mu_b^2}{2\sigma_T^2}$$

Also recall Eq. (3):

$$\sigma_T^2 = \sigma^2 + \sigma_b^2 = \sigma^2 + Np^2 \quad (10)$$

where N is the number of identical small bubbles and p^2 is the average rf intensity scattered by one such bubble. This substitution follows Rayleigh's original formulation which is done here to illustrate the measurement proportion. Thus:

$$F(\mu_b) \doteq \frac{\mu_b^2}{2\sigma^2} \left(1 - \frac{Np^2}{\sigma^2} \right) \quad (11)$$

Since $Np^2 \ll \sigma^2$ a further simplification can be made:

$$F(\mu_b) = \frac{\mu_b^2}{2\sigma^2} \left(1 - \frac{Np^2}{\sigma^2} \right) \quad (12)$$

This equation shows that the baseline of the measurement is proportional to:

$$\mu_b^2 / (2\sigma^2) \quad ; \quad (13)$$

Changes from this baseline are proportional to the number and the scattering strength of the bubbles:

$$\frac{\mu_b^2}{2\sigma^2} \cdot \frac{1}{\sigma^2} \cdot \underbrace{Np^2} \quad (14)$$

Based on this structure for measurements the net formation of isolated small bubbles during decompression is monotonic up to the time when resorption ensues as dominant. Consequently the instrument's output should follow suit; in this way movement artifacts can be more readily identified and bubble formation between the skin-transducer interface can be easily diagnosed.

By September of 1982 it became clear that we had previously set our threshold for detection of bubbles of the order of 20 to 30 times too high and that the integrator had to be further modified. Thus, with the threshold set quite low, although it was feared it might be too sensitive, 4 possible baseline settings were contemplated. These correspond to the region of backscatter amplitudes where bubble scattering is located.

In October of 1982, we set the baseline for the most sensitive setting and on October 29th, the first test was made. Since on the first test we had not had time to establish a formal baseline, we presumed that the drift we saw (in the direction of bubble formation) was simply baseline drift. Later, after a second experiment was carried out with a steady baseline present it was discovered that the deviation of the chart recorder print was indeed due to bubbles.

Seven human subjects were exposed to pressures from the equivalent of 11 meters to 50 meters of seawater for periods which ranged from 20 minutes to 5.5 hours. Twelve experimental trials were made from which satisfactory recordings could be obtained. With the ultrasonic transducer (without the water-filled stand off) affixed to the right calf of each subject, with movement minimized by the full length plastic leg cast, a baseline was usually established on the recording graph for 15 to 30 minutes before decompression began.

It is calculated that the instrument is able to detect bubbles of two microns size or larger or clusters of bubbles. The tissue slice interrogated measures 7 cm in depth by 5 cm in length by 2 mm in width.

Results

Appended are representative graphs showing bubble formation during decompression and the suppression of bubbles with recompression. (Figures 6-10, Appendix XIII) Bubbles were uniformly recorded on decompressions from all pressures tested when the exposure time had been greater than one hour. Bubbles could not be detected in short halftime tissues after shorter exposures even following dives to 50 meters.

We now feel that we can demonstrate bubbles appearing immediately as decompression commences and continue to grow and that these bubbles are diminished on recompression. We also ran studies on 2 occasions shifting the patient to helium isobarically at depths of 24.2M (80 ft.) and 50M (165 ft.). On neither occasion did we detect bubbles following the isobaric shift to helium from air. However, as we decompressed from these pressures, bubbles appeared. (Figure 11, Appendix XIII)

In summary, we feel we have developed a method for detecting stationary bubbles in asymptomatic humans. The present drawbacks or limitations are several: 1. transducer movement must be absolutely avoided or the results cannot be reproduced. 2. any movement of the subject during the course of the scanning may result in the sudden dislodging or disappearance of bubbles as detected by the scanner. 3. at the present state of development we cannot quantify or discern the severity of bubble formation or relate the rate of increase in bubbles to the severity of the decompression.

Further work will have to be carried out to refine this technique enabling us to use it for monitoring of decompression under practical conditions or make it useful in the development of decompression tables.

Discussion & Conclusions

In our research to develop a set decompression schedule which would be superior in removing nitrogen from the body, we carried out 182 actual compression/decompressions.

The results of the nitrogen washout studies from 36 dives based on statistical analysis, show an insignificant difference between using OSHA and Autodec II air decompression schedules ($p = 0.4540$) in denitrogenation. Therefore, the use of Autodec II air tables in place of the OSHA schedule for caisson workers would be of little benefit viewed solely from objective evidence. However, our results on the Autodec III (oxygen) schedule compared to the OSHA decompression schedule did show a statistical difference ($p = 0.0850$). It is our conviction that presently the Autodec III oxygen table represents the best available replacement for the current OSHA tables.

Autodec III (oxygen) combines the use of O₂ and stage decompression, which we believe have synergistic effects in increasing nitrogen elimination during decompression.

Initial reluctance to implement the new Autodec III - O₂ schedule may be encountered for a number of reasons. It will be slightly more expensive for construction companies to provide the additional O₂ and safety devices to insure against fire hazard. In addition, the change in a decompression protocol, like any new protocol, may cause some initial resistance in the training of the tunneling or caisson crews. However, the advantage of reducing the unacceptably high incidence of osteonecrosis far outweighs such considerations.

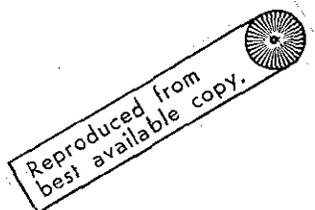
It is interesting to note that since 1907, our knowledge of diving physiology and decompression procedures has lagged, in the compressed air industry, 20 years or more behind the commercial diving world. Physiologically based decompression started in naval diving in 1907 was not even attempted in caisson and tunnel work until 1963.

With regard to oxygen decompression, it has been used in naval diving for over 40 years, but its used in caissons (where decompressions tend to be even more severe) was not even considered until the present time.

Tradition and ignorance have often lain behind failure to adopt more sophisticated technology - even when pain and suffering could be eliminated or decreased. There is a parallel in the diving industry. In 1939, oxygen treatment of decompression sickness was rejected by the U.S. Navy for general use, despite excellent experimental results, because of "the fire danger" - "oxygen toxicity" and the possibility of its being used by inadequately trained personnel. In 1967, oxygen therapy of bends became the Navy Standard (with a 13 times higher success rate) using the same oxygen, the same patients, the same chambers and the same personnel.

Appropriate instructions and procedures for tunnel workers using oxygen decompression are appended to this report. These have been reviewed and approved in their final form by operating tunnel contractors - after consultation with OSHA field inspectors.

The Edel-Kindwall Caisson Tables using oxygen [Autodec III (O₂)] represent the only decompression tables for compressed air workers that have been tested in the laboratory before being released for use in the field.



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APPENDIX I

EDEL-KINDWALL CAISSON TABLE (OXYGEN)
(AUTODEC III)

DEPTH TIME	ASCENT (D E C O M P R E S S I O N							S T O P S)		TOTAL hrs.		
	psi min.	hrs.	to 1st stop	40	36	32	28	24	20	16	12	8		4	
12	7.5	3												0	3
12	8.0	2											5/ 5	0	13
14	4.5	4												0	4
14	5.0	3											5/ 5	0	14
14	5.5	3											5/10	0	19
14	6.0	3											5/10	0	19
14	6.5	3											5/15	0	24
14	7.0	3											5/20	0	29
14	7.5	3											5/25	0	34
14	8.0	3											5/30	0	39
16	3.0	4												0	4
16	3.5	3											5/ 0	0	9
16	4.0	3											5/10	0	19
16	4.5	3											5/15	0	24
16	5.0	3											5/20	0	29
16	5.5	3											5/30	0	39
16	6.0	3											5/30	0	39
16	6.5	3											5/30	0	39
16	7.0	2										5/ 0	0/30	0	39
16	7.5	2										5/ 0	0/40	0	49
16	8.0	2										5/ 0	0/40	0	49
18	2.5	5												0	5
18	3.0	4											5/10	0	20
18	3.5	4											5/15	0	25
18	4.0	4											5/25	0	35
18	4.5	4											5/30	0	40
18	5.0	4											5/35	0	45
18	5.5	3										5/ 0	0/40	0	50
18	6.0	3										5/ 0	0/40	0	50
18	6.5	3										5/ 0	0/45	0	55
18	7.0	3										5/ 0	0/45	0	55
18	7.5	3										5/ 0	0/50	1	0
18	8.0	3										5/ 0	0/60	1	10

APPENDIX I

EDEL-KINDWALL CAISSON TABLE (OXYGEN)
(AUTODEC III)

TIME ASCENT to 1st hrs. stop	D E C O M P R E S S I O N											S T O P S		TOTAL TIME hrs. min.
	40	36	32	28	24	20	16	12	8	4				
2.0	5												0	5
2.5	4												5/10	0 20
3.0	3											5/0	0/15	0 25
3.5	3											5/0	0/25	0 35
4.0	3											5/0	0/30	0 40
4.5	3											5/0	0/40	0 50
5.0	3											5/0	0/45	0 55
5.5	3											5/0	0/50	1 0
6.0	3											5/0	0/50	1 0
6.5	3											15/0	0/60	1 20
7.0	2								5/0			0/15	5/50	1 20
7.5	2								5/0			0/15	0/60	1 25
8.0	2								5/0			0/20	0/60	1 30
22	1.5	6												0 6
22	2.0	5											15/0	0 21
22	2.5	4										5/0	0/15	0 26
22	3.0	4										5/0	0/25	0 36
22	3.5	4										5/0	0/35	0 46
22	4.0	4										5/0	0/45	0 56
22	4.5	4										10/0	0/50	1 6
22	5.0	4										15/0	0/50	1 11
22	5.5	3							5/0			0/15	5/50	1 21
22	6.0	3							5/0			0/20	5/50	1 26
22	6.5	3							5/0			0/25	5/60	1 41
22	7.0	3							5/0			0/25	5/60	1 41
22	7.5	3							5/0			0/30	5/0	1 46
22	8.0	3							5/0			0/30	5/70	1 56

42
112
60
52

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EDEL-KINDWALL CAISSON TABLE (OXYGEN)
(AUTODEC III)

DEPTH psi	TIME hrs.	ASCENT to 1st stop	D E C O M P R E S S I O N								S T O P S			TOTAL TIME	
			40	36	32	28	24	20	16	12	8	4	hrs.	min.	
24	1.0	6												0	6
24	1.5	5											10/ 0	0	16
24	2.0	4									5/ 0	0/10		0	21
24	2.5	4									5/ 0	0/20		0	31
24	3.0	4									5/ 0	0/35		0	46
24	3.5	4									10/ 0	0/45		1	1
24	4.0	3								5/ 0	0/10	0/50		1	11
24	4.5	3								5/ 0	0/15	0/50		1	16
24	5.0	3								5/ 0	0/20	5/50		1	26
24	5.5	3								5/ 0	0/25	5/60		1	41
24	6.0	3								5/ 0	0/30	5/60		1	46
24	6.5	3								5/ 0	0/35	5/60		1	51
24	7.0	3								5/ 0	0/40	5/60		1	56
24	7.5	2							5/ 0	0/ 5	0/35	10/70		2	11
24	8.0	2							5/ 0	0/ 5	0/60	5/60		2	21
6	0.5	7												0	7
6	1.0	6										5/ 0		0	12
6	1.5	5									5/ 0	0/ 5		0	17
6	2.0	5									5/ 0	0/20		0	32
6	2.5	5									5/ 0	0/30		0	42
6	3.0	4								5/ 0	0/10	0/40		1	2
6	3.5	4								5/ 0	0/15	5/45		1	17
6	4.0	4								5/ 0	0/20	5/50		1	27
6	4.5	4								5/ 0	0/25	5/50		1	32
6	5.0	4								5/ 0	0/35	5/50		1	42
6	5.5	4								5/ 0	0/40	5/60		1	57
6	6.0	3							5/ 0	0/ 5	0/40	5/60		2	2
6	6.5	3							5/ 0	0/10	0/40	5/70		2	17
6	7.0	3							5/ 0	0/10	0/45	5/70		2	22
6	7.5	3							5/ 0	0/15	5/60	5/60		2	37
6	8.0	3							5/ 0	0/20	5/60	5/70		2	52

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EDEL-KINDWALL CAISSON TABLE (OXYGEN)
(AUTODEC III)

DEPTH psi	TIME hrs.	ASCENT to lsa stop	D E C O M P R E S S I O N										S T O P S		TOTAL TIME hrs. min.		
			40	36	32	28	24	20	16	12	8	4	hrs.	min.			
28	0.5	7														0	7
28	1.0	6														10/0	0 17
28	1.5	5											5/0		0/10	0	22
28	2.0	5											5/0		0/30	0	42
28	2.5	4									5/0		0/10		0/30	0	52
28	3.0	4									5/0		0/15		0/45	1	12
28	3.5	4									5/0		0/20		5/50	1	27
28	4.0	4									5/0		0/30		5/50	1	37
28	4.5	4									10/0		0/40		5/50	1	52
28	5.0	3								5/0	0/10		0/40		5/50	1	57
28	5.5	3								5/0	0/10		0/40		5/60	2	12
28	6.0	3								5/0	0/15		5/40		5/70	2	27
28	6.5	3								5/0	0/20		5/40		5/70	2	32
28	7.0	3								5/0	0/25		5/60		5/60	2	47
28	7.5	2							5/0	0/5	0/20		5/60		5/70	2	57
28	8.0	2							5/0	0/5	0/50		5/60		5/60	3	22
30	0.5	8														0	8
30	1.0	6											5/0		0/5	0	18
30	1.5	6											5/0		0/15	0	28
30	2.0	5									5/0		0/5		0/30	0	48
30	2.5	5									5/0		0/15		0/40	1	8
30	3.0	5									5/0		0/20		5/45	1	23
30	3.5	5									10/0		0/30		5/45	1	38
30	4.0	4								5/0	0/10		0/30		5/50	1	48
30	4.5	4								5/0	0/15		5/40		5/50	2	8
30	5.0	4								5/0	0/15		5/40		5/60	2	18
30	5.5	4								5/0	0/20		5/40		5/70	2	33
30	6.0	4								5/0	0/25		5/40		10/70	2	43
30	6.5	4								5/0	0/30		5/60		5/60	2	53
30	7.0	3							5/0	0/5	0/30		5/60		5/70	3	8
30	7.5	3							5/0	0/5	0/50		5/60		5/60	3	18
30	8.0	3							5/0	0/5	0/50		5/60		10/70	3	33

APPENDIX I

EDEL-KINDWALL CAISSON TABLE (OXYGEN)
(AUTODEC III)

DEPTH psi	TIME hrs.	ASCENT to 1st stop	D E C O M P R E S S I O N								S T O P S			TOTAL TIME	
			40	36	32	28	24	20	16	12	8	4	hrs.	min.	
32	0.5	8												0	8
32	1.0	6												0	18
32	1.5	5								5/ 0	0/ 5	0/15		0	33
32	2.0	5								5/ 0	0/10	0/25		0	48
32	2.5	5								5/ 0	0/20	0/40		1	13
32	3.0	4							5/ 0	0/ 5	0/25	5/45		1	33
32	3.5	4							5/ 0	0/10	0/30	5/45		1	43
32	4.0	4							5/ 0	0/15	5/35	5/50		2	3
32	4.5	4							5/ 0	0/20	5/40	5/60		2	23
32	5.0	4							5/ 0	0/25	5/40	5/60		2	28
32	5.5	3						5/ 0	0/ 5	0/25	5/40	5/70		2	43
32	6.0	3						5/ 0	0/ 5	0/30	5/60	5/60		2	58
32	6.5	3						5/ 0	0/10	0/50	5/60	5/60		3	23
32	7.0	3						5/ 0	0/10	0/50	5/60	5/70		3	33
32	7.5	2					5	0/ 5	0/40	5/50	5/60	5/60		4	3
32	8.0	2					5	0/ 5	0/40	5/50	5/60	5/70		4	13
34	0.5	9												0	9
34	1.0	7									5/ 0	0/10		0	24
34	1.5	6								5/ 0	0/ 5	0/20		0	39
34	2.0	6								5/ 0	0/15	0/35		1	4
34	2.5	5							5/ 0	0/ 5	0/20	5/40		1	24
34	3.0	5							5/ 0	0/10	0/30	5/45		1	44
34	3.5	5							5/ 0	0/15	5/35	5/50		2	4
34	4.0	5							5/ 0	0/20	5/40	5/50		2	14
34	4.5	5							5/ 0	0/25	5/40	5/60		2	29
34	5.0	4						5/ 0	0/10	0/25	5/40	5/70		2	49
34	5.5	4						5/ 0	0/10	0/35	5/40	10/70		3	4
34	6.0	4						5/ 0	0/15	5/30	5/50	5/70		3	24
34	6.5	4						5/ 0	0/20	5/50	5/60	5/70		3	49
34	7.0	3					5	0/ 5	0/40	5/50	5/60	5/70		4	4
34	7.5	3					5	0/35	5/40	5/50	5/60	5/70		4	39
34	8.0	3					5	0/35	5/40	5/50	5/60	5/70		4	49

APPENDIX I

EDEL-KINDWALL CAISSON TABLE (OXYGEN)
(AUTODEC III)

DEPTH fath	TIME hrs.	ASCENT to 1st stop	D E C O M P R E S S I O N										S T O P S		TOTAL TIME hrs. min		
			40	36	32	28	24	20	16	12	8	4	hrs.	min			
36	0.5	9														0	9
36	1.0	6									5/ 0	0/ 5	0/ 5			0	24
36	1.5	6									5/ 0	0/ 10	0/ 25			0	49
36	2.0	5									5/ 0	0/ 15	0/ 35			1	9
36	2.5	5									5/ 0	0/ 20	5/ 45			1	34
36	3.0	5									5/ 0	0/ 15	5/ 25	5/ 50		1	54
36	3.5	5									10/ 0	0/ 20	5/ 40	5/ 50		2	19
36	4.0	4							5/ 0	0/ 10	0/ 20	5/ 40	5/ 60			2	34
36	4.5	4							5/ 0	0/ 10	0/ 25	5/ 40	5/ 65			2	44
36	5.0	4							5/ 0	0/ 15	5/ 30	5/ 40	5/ 70			3	4
36	5.5	4							5/ 0	0/ 20	5/ 30	5/ 60	5/ 70			3	29
36	6.0	3						5	0/ 5	0/ 15	5/ 50	5/ 60	5/ 70			3	49
36	6.5	3						5	0/ 5	5/ 40	5/ 50	5/ 60	5/ 70			4	19
36	7.0	3						5	0/ 35	5/ 40	5/ 50	5/ 60	5/ 70			4	49
36	7.5	3						5	0/ 35	5/ 40	5/ 50	5/ 60	10/ 70			4	54
36	8.0	2				5	5	0/ 35	5/ 40	10/ 50	10/ 60	40/ 70				5	39
38	0.5	9											10/ 0			0	20
38	1.0	7								5/ 0	0/ 5	0/ 10				0	30
38	1.5	6								5/ 0	0/ 5	0/ 10	0/ 20			0	50
38	2.0	6								5/ 0	0/ 10	0/ 15	0/ 40			1	20
38	2.5	6								5/ 0	0/ 15	5/ 25	5/ 40			1	45
38	3.0	5							5/ 0	0/ 5	0/ 15	5/ 30	5/ 50			2	5
38	3.5	5							5/ 0	0/ 10	0/ 20	0/ 35	5/ 50			2	15
38	4.0	5							5/ 0	0/ 15	0/ 20	5/ 40	5/ 70			2	50
38	4.5	5							5/ 0	0/ 20	0/ 30	5/ 40	5/ 70			3	5
38	5.0	5							5/ 0	0/ 20	5/ 35	5/ 60	5/ 60			3	25
38	5.5	4						5	0/ 5	0/ 20	5/ 50	5/ 60	5/ 60			3	45
38	6.0	4						5	0/ 5	5/ 40	5/ 50	5/ 60	5/ 60			4	10
38	6.5	4						5	0/ 35	5/ 40	5/ 50	5/ 60	5/ 70			4	50
38	7.0	3				5	5	0/ 35	5/ 40	5/ 50	5/ 60	5/ 70				4	55
38	7.5	3				5	10	0/ 35	5/ 40	10/ 50	10/ 60	50/ 70				5	55
38	8.0	3				5	15	0/ 35	5/ 40	15/ 50	15/ 60	80/ 70				6	40

APPENDIX I

EDEL-KINDWALL CAISSON TABLE (OXYGEN)
(AUTODEC III)

DEPTH psi	TIME ASCENT to 1st hrs. stop	D E C O M P R E S S I O N										S T O P S		TOTAL TI hrs. mi		
		40	36	32	28	24	20	16	12	8	4	hrs.	mi			
36	0.5	9													0	9
36	1.0	6									5/0	0/5	0/5		0	24
36	1.5	6									5/0	0/10	0/25		0	49
36	2.0	5								5/0	0/5	0/15	0/35		1	9
36	2.5	5								5/0	0/10	0/20	5/45		1	34
36	3.0	5								5/0	0/15	5/25	5/50		1	54
36	3.5	5								10/0	0/20	5/40	5/50		2	19
36	4.0	4						5/0	0/10	0/20	5/40	5/60			2	34
36	4.5	4						5/0	0/10	0/25	5/40	5/65			2	44
36	5.0	4						5/0	0/15	5/30	5/40	5/70			3	4
36	5.5	4						5/0	0/20	5/30	5/60	5/70			3	29
36	6.0	3					5	0/5	0/10	5/50	5/60	5/70			3	49
36	6.5	3					5	0/5	5/10	5/30	5/60	5/70			4	19
36	7.0	3					5	0/35	5/40	5/50	5/60	5/70			4	49
36	7.5	3					5	0/35	5/40	5/50	5/60	10/70			4	54
36	8.0	2			5	5	0/35	5/40	10/50	10/60	40/70				5	39
38	0.5	9											10/0		0	20
38	1.0	7								5/0	0/5	0/10			0	30
38	1.5	6							5/0	0/5	0/10	0/20			0	50
38	2.0	6							5/0	0/10	0/15	0/40			1	20
38	2.5	6							5/0	0/15	5/25	5/40			1	45
38	3.0	5						5/0	0/5	0/15	5/30	5/50			2	5
38	3.5	5						5/0	0/10	0/20	0/35	5/50			2	15
38	4.0	5						5/0	0/15	0/20	5/40	5/70			2	50
38	4.5	5						5/0	0/20	0/30	5/40	5/70			3	5
38	5.0	5						5/0	0/20	5/35	5/60	5/60			3	25
38	5.5	4					5	0/5	0/20	5/50	5/60	5/60			3	45
38	6.0	4					5	0/5	5/40	5/50	5/60	5/60			4	10
38	6.5	4					5	0/35	5/40	5/50	5/60	5/70			4	50
38	7.0	3			5	5	0/35	5/40	5/50	5/60	5/70				4	55
38	7.5	3			5	10	0/35	5/40	10/50	10/60	50/70				5	55
38	8.0	3			5	15	0/35	5/40	15/50	15/60	80/70				6	40

APPENDIX I

EDEL-KINDWALL CAISSON TABLE (OXYGEN)
(AUTODEC III)

DEPTH psi	TIME hrs.	ASCENT to lst stop	D E C O M P R E S S I O N										S T O P S		TOTAL TIME hrs. min		
			40	36	32	28	24	20	16	12	8	4	hrs.	min			
40	0.5	8												5/ 0	0/ 5	0	20
40	1.0	7												5/ 0	0/ 5	0	35
40	1.5	6								5/ 0	0/ 5	0/10	0/30			1	0
40	2.0	6								5/ 0	0/10	0/20	5/40			1	30
40	2.5	5							5/ 0	0/ 5	0/15	5/25	5/40			1	50
40	3.0	5							5/ 0	0/10	0/15	5/35	5/50			2	15
40	3.5	5							5/ 0	0/15	5/20	5/35	5/60			2	40
40	4.0	5							5/ 0	0/20	5/25	5/40	5/70			3	5
40	4.5	4						5	0/ 5	0/20	5/30	5/40	5/70			3	15
40	5.0	4						5	0/10	0/20	5/30	5/60	10/70			3	45
40	5.5	4						5	0/10	0/25	5/50	5/60	5/70			4	5
40	6.0	3				5	5	0/10	0/40	5/50	5/60	5/70			4	25	
40	6.5	3				5	10	0/35	5/40	5/50	5/60	20/70			5	15	
40	7.0	3				5	15	0/35	5/40	10/50	10/60	60/70			6	10	
40	7.5	3				5	20	0/35	5/40	15/50	15/60	90/70			6	55	
40	8.0	2		5	5	30	0/35	5/40	20/50	20/60	150/70			8	20		
42	0.5	9												5/ 0	0/ 5	0	21
42	1.0	7								5/ 0	0/ 5	0/ 5	0/15			0	41
42	1.5	6							5/ 0	0/ 5	0/ 5	0/10	0/30			1	6
42	2.0	6							5/ 0	0/ 5	0/10	0/25	5/40			1	41
42	2.5	6							5/ 0	0/10	0/15	5/25	5/50			2	6
42	3.0	6							5/ 0	0/15	5/20	5/30	5/50			2	26
42	3.5	6							10/ 0	0/15	5/30	5/40	5/60			3	1
42	4.0	5						5	0/ 5	0/20	5/30	5/40	5/70			3	16
42	4.5	5						5	0/10	0/20	5/30	5/45	30/70			3	51
42	5.0	5						5	0/15	5/20	5/35	5/60	20/70			4	11
42	5.5	4				5	5	0/15	5/25	5/50	5/60	10/70			4	26	
42	6.0	4				5	5	0/35	5/40	5/50	5/60	5/70			4	56	
42	6.5	4				5	10	0/35	5/40	10/50	10/60	60/70			6	6	
42	7.0	3		5	5	15	0/35	5/40	15/50	15/60	100/70			7	6		
42	7.5	3		5	5	20	0/35	5/40	20/50	20/60	150/70			8	11		
42	8.0	3		5	5	30	0/35	5/40	30/50	30/60	200/70			9	31		

APPENDIX I

EDEL-KINDWALL CAISSON TABLE (OXYGEN)
(AUTODEC III)

TIME ASCENT to 1st hrs. stop	D E C O M P R E S S I O N											S T O P S		TOTAL TIME	
	40	36	32	28	24	20	16	12	8	4	hrs.	min.	hrs.	min.	
0.5	8							5/ 0	0/ 5	0/ 5	0	26			
1.0	7						5/ 0	0/ 5	0/ 5	0/15	0	41			
1.5	6					5/ 0	0/ 5	0/ 5	5/15	5/30	1	21			
2.0	6					5/ 0	0/ 5	0/15	5/20	5/40	1	46			
2.5	6					5/ 0	0/ 5	0/10	0/20	5/30	1	26			
3.0	5				5	0/ 5	0/15	5/20	5/35	5/50	2	36			
3.5	5				5	0/10	0/15	5/25	5/40	5/60	3	1			
4.0	5				5	0/10	0/20	5/30	5/40	5/70	3	21			
4.5	4			5	10	0/15	5/20	5/35	5/60	5/70	4	6			
5.0	4			5	10	0/15	5/30	5/50	5/60	5/70	4	31			
5.5	4			5	10	0/35	5/40	5/50	5/60	5/60	4	51			
6.0	3		5	10	15	0/35	5/40	10/50	10/60	60/70	6	21			
6.5	3		5	10	15	0/35	5/40	15/50	15/60	100/70	7	11			
7.0			5	10	20	0/35	5/40	20/50	20/60	150/70	8	16			
7.5	3		5	10	30	0/35	5/40	30/50	30/60	200/70	9	36			
8.0	2	5	10	15	30	45/35	45/40	45/50	45/60	720/ 0	19	16			
0.5	9							5/ 0	0/ 5	0/ 5	0	27			
1.0	8						5/ 0	0/ 5	0/10	0/15	0	47			
1.5	7					5/ 0	0/ 5	0/ 5	0/20	5/30	1	22			
2.0	6				5	0/ 5	0/ 5	0/15	5/20	5/45	1	57			
2.5	6				5	0/ 5	0/10	0/20	5/30	5/50	2	22			
3.0	6				5	0/10	0/15	5/20	5/40	5/60	2	57			
3.5	6				5	0/10	0/15	5/25	5/40	5/70	3	17			
4.0	5			5	10	0/15	5/20	5/30	5/60	5/70	4	2			
4.5	5			5	10	0/20	5/20	5/50	5/60	5/70	4	27			
5.0	5			5	15	0/35	5/40	5/50	5/60	5/70	5	7			
5.5	4		5	10	20	0/35	5/40	10/50	10/60	50/70	6	17			
6.0	4		5	10	30	0/35	5/40	15/50	15/60	90/70	7	17			
6.5	4		5	10	30	0/35	5/40	20/50	20/60	150/70	8	27			
7.0	3	5	10	15	40	0/35	5/40	30/50	30/60	200/70	10	2			
7.5	3	5	10	15	40	45/35	45/40	45/50	45/60	720/ 0	19	27			
8.0	3	5	10	15	50	60/35	60/40	60/50	60/60	720/ 0	20	37			

APPENDIX I

EDEL-1 DWALL CAISSON TABLE (OXYGEN)
(AUTODEC III)

TIME ASCENT to 1st hrs. stop	D E C O M P R E S S I O N											S T O P S		TOTAL TIME hrs. min
	40	36	32	28	24	20	16	12	8	4				
0.5	8						5/ 0	0/ 5	0/ 5	0/ 5			0	32
1.0	7						5/ 0	0/ 5	0/ 5	0/15	0/20		1	2
1.5	6					5	0/ 5	0/ 5	0/ 5	5/20	5/35		1	37
2.0	6					5	0/ 5	0/ 5	0/15	5/25	5/50		2	7
2.5	6					5	0/ 5	0/15	5/20	5/30	5/50		2	32
3.0	5			5	10		0/10	0/15	5/25	5/40	5/60		3	12
3.5	5			5	10		0/15	5/15	5/30	5/40	5/70		3	37
4.0	5			5	15		0/15	5/25	5/30	5/60	5/70		4	12
4.5	4		5	5	15		0/20	5/40	5/50	5/60	5/60		4	47
5.0	4		5	5	30		0/35	5/40	10/50	10/60	10/70		5	42
5.5	4		5	10	30		0/35	5/40	15/50	15/60	90/70		7	17
6.0	3	5	5	10	40		0/35	5/40	20/50	20/60	120/70		8	17
6.5	3	5	5	10	60		0/35	5/40	30/50	30/60	180/70		9	52
7.0	3	5	10	15	60	45/35	45/40	45/50	45/60	720/ 0		19	47	
7.5	3	5	10	15	70	60/35	60/40	60/50	60/60	720/ 0		20	57	
8.0	2	5	5	10	15	70	60/35	60/40	60/50	60/60	780/ 0		22	2
0.5	9						5/ 0	0/ 5	0/ 5	0/10			0	38
1.0	8						5/ 0	0/ 5	0/ 5	0/20	0/20		1	8
1.5	7				5		0/ 5	0/ 5	0/10	0/20	5/35		1	38
2.0	7				5		0/ 5	0/10	0/15	5/25	5/50		2	13
2.5	6			5	5		0/10	0/15	5/15	5/35	5/60		2	53
3.0	6			5	10		0/10	0/20	5/25	5/40	5/70		3	28
3.5	6			5	15		0/15	5/20	5/35	5/60	5/60		4	3
4.0	5		5	5	20		0/20	5/25	5/50	5/60	5/60		4	32
4.5	5		5	5	30		0/35	5/40	10/50	10/60	10/70		5	43
5.0	5		5	5	40		0/35	5/40	15/50	15/60	60/70		6	53
5.5	4	5	5	10	45		0/35	5/40	20/50	20/60	120/70		8	18
6.0	4	5	5	15	60		0/35	5/40	30/50	30/60	180/70		9	58
6.5	4	5	5	20	70	45/35	45/40	45/50	45/60	720/ 0		19	58	
7.0	3	5	5	10	20	70	60/35	60/40	60/50	60/60	720/ 0		21	8
7.5	3	5	5	10	30	70	60/35	60/40	60/50	60/60	780/ 0		22	18
8.0	3	5	5	10	40	70	60/35	60/40	60/50	540/ 0	300/70		22	38

tested - these tables were not tested as they are not commercially usable. The risk of
 necrosis to the test subjects (always present when testing new tables at high
 pressure) was not adjudged reasonable on a risk-versus-benefit basis. The reason they are not
 used in the field is that decompression time exceeds working time.

APPENDIX II

EDEL-KINDWALL CAISSON TABLE (AIR)
(AUOTDEC III)

TIME ASCENT to 1st hrs. stop	D E C O M P R E S S I O N							S T O P S			TOTAL TIME	
	40	36	32	28	24	20	16	12	8	4	hrs.	min.
7.5	3										0	3
8.0	2									10	0	13
4.5	4										0	4
5.0	3									10	0	14
5.5	3									20	0	24
6.0	3									30	0	34
6.5	3									40	0	44
7.0	3									45	0	49
7.5	3									50	0	54
8.0	3									60	1	4
3.0	4										0	4
3.5	3									5	0	9
4.0	3									20	0	24
4.5	3									40	0	44
5.0	3									50	0	54
5.5	3									70	1	14
6.0	3									80	1	24
6.5	3									80	1	24
7.0	2							5		80	1	29
7.5	2							5		90	1	39
8.0	2							5		100	1	49
2.5	5										0	5
3.0	4									15	0	20
3.5	4									40	0	45
4.0	4									60	1	5
4.5	4									80	1	25
5.0	4									90	1	35
5.5	3							5		90	1	40
6.0	3							5		100	1	50
6.5	3							5		110	2	0
7.0	3							5		120	2	10
7.5	3							5		140	2	30
8.0	3							5		150	2	40

APPENDIX II

EDEL-KINDWALL CAISSON TABLE (AIR)
(AUTODEC III)

TIME ASCENT to 1st. hrs. stop	D E C O M P R E S S I O N											TOTAL TIME	
	40	36	32	28	24	20	16	12	8	4	hrs.	min.	
2.0	5										0	5	
2.5	4									20	0	25	
3.0	3								5	40	0	50	
3.5	3								5	60	1	10	
4.0	3								5	80	1	30	
4.5	3								5	100	1	50	
5.0	3								5	110	2	0	
5.5	3								5	120	2	10	
6.0	3								5	140	2	30	
6.5	3								15	140	2	40	
7.0	2							5	40	150	3	20	
7.5	2							5	45	150	3	25	
8.0	2							5	50	180	4	0	
1.5	6										0	6	
2.0	5									15	0	21	
2.5	4								5	40	0	51	
3.0	4								5	60	1	11	
3.5	4								5	90	1	41	
4.0	4								5	110	2	1	
4.5	4								10	120	2	16	
5.0	4								15	150	2	51	
5.5	3							5	40	150	3	21	
6.0	3							5	50	150	3	31	
6.5	3							5	60	180	4	11	
7.0	3							5	70	180	4	21	
7.5	3							5	80	180	4	31	
8.0	3							5	90	180	4	41	

APPENDIX II

EDEL-KINDWALL CAISSON TABLE (AIR)
(AUTODEC III)

TIME ASCENT (to 1st		D E C O M P R E S S I O N							S T O P S				TOTAL TIME	
hrs.	stop	40	36	32	28	24	20	16	12	8	4	hrs.	min	
1.0	6											0	6	
1.5	5										10	0	16	
2.0	4									5	30	0	41	
2.5	4									5	60	1	11	
3.0	4									5	90	1	41	
3.5	4									10	120	2	16	
4.0	3								5	30	150	3	11	
4.5	3								5	40	150	3	21	
5.0	3								5	60	180	4	11	
5.5	3								5	70	180	4	21	
6.0	3								5	80	180	4	31	
6.5	3								5	90	180	4	41	
7.0	3								5	100	180	4	51	
7.5	2							5	5	120	240	6	16	
8.0	2							5	5	120	240	6	16	
0.5	7											0	7	
1.0	6										5	0	12	
1.5	5									5	10	0	22	
2.0	5									5	40	0	52	
2.5	5									5	80	1	32	
3.0	4								5	15	140	2	47	
3.5	4								5	40	150	3	22	
4.0	4								5	60	150	3	42	
4.5	4								5	70	150	3	52	
5.0	4								5	90	180	4	42	
5.5	4								5	100	180	4	52	
6.0	3							5	15	100	180	5	7	
6.5	3							5	30	120	210	6	12	
7.0	3							5	30	120	240	6	42	
7.5	3							5	40	120	240	6	52	
8.0	3							5	45	120	300	7	57	

APPENDIX II

EDEL-KINDWALL CAISSON TABLE (AIR)
(AUTODEC III)

DEPTH psi	TIME ASCENT to lst. hrs. stop	D E C O M P R E S S I O N											S T O P S		TOTAL TIME	
		40	36	32	28	24	20	16	12	8	4	hrs.	min.			
28	0.5	7													0	7
28	1.0	6													10	0 17
28	1.5	5												5	30	0 42
28	2.0	5												5	60	1 12
28	2.5	4									5	15	120		2 27	
28	3.0	4									5	40	120		2 52	
28	3.5	4									5	60	150		3 42	
28	4.0	4									5	80	150		4 2	
28	4.5	4									10	90	180		4 47	
28	5.0	3							5		20	100	180		5	
28	5.5	3							5		30	120	210		6 12	
28	6.0	3							5		40	120	240		6 52	
28	6.5	3							5		60	120	240		7 12	
28	7.0	3							5		60	150	240		7 42	
28	7.5	2							5	5	70	150	300		8 57	
28	8.0	2							5	5	70	150	360		9 57	
20	0.5	8													0	8
20	1.0	6												5	10	0 23
20	1.5	6												5	40	0 53
20	2.0	5									5	10	70		1 33	
20	2.5	5									5	30	120		2 43	
20	3.0	5									5	60	120		3 13	
20	3.5	5									10	70	150		3 53	
20	4.0	4							5		20	90	160		4 43	
20	4.5	4							5		30	120	180		5 43	
20	5.0	4							5		40	120	210		6 23	
20	5.5	4							5		60	120	240		7 13	
20	6.0	4							5		70	150	240		7 53	
20	6.5	4							5		80	150	240		8 33	
20	7.0	3							5	5	90	150	300		9 13	
20	7.5	3							5	5	90	150	360		10 13	
20	8.0	3							5	15	100	180	*540		14 8	

includes 8 hrs. sleeping time.

APPENDIX II

EDEL-KINDWALL CAISSON TABLE (AIR)
(AUTODEC III)

TIME ASCENT to lst. hrs. stop	D E C O M P R E S S I O N											TOTAL TIME	
	40	36	32	28	24	20	16	12	8	4	hrs.	min.	
0.5	8										0	8	
1.0	6								5	15	0	28	
1.5	5							5	5	45	1	3	
2.0	5							5	20	80	1	53	
2.5	5							5	45	120	2	58	
3.0	4						5	15	60	150	3	58	
3.5	4						5	20	90	150	4	33	
4.0	4						5	40	120	180	5	53	
4.5	4						5	50	120	210	6	33	
5.0	4						5	70	120	240	7	23	
5.5	3					5	10	80	150	240	8	13	
6.0	3					5	15	90	150	240	8	28	
6.5	3					5	20	100	150	300	9	43	
7.0	3					5	30	120	150	360	11	13	
7.5	2					5	5	40	120	180	*600	15	58
8.0	2					5	5	40	120	180	*660	16	58
0.5	9										0	9	
1.0	7								5	20	0	34	
1.5	6							5	10	60	1	24	
2.0	6							5	30	120	2	44	
2.5	5						5	10	60	150	3	54	
3.0	5						5	30	70	150	4	24	
3.5	5						5	40	100	180	5	34	
4.0	5						5	60	120	180	6	14	
4.5	5						10	70	120	240	7	29	
5.0	4					5	20	80	150	240	8	24	
5.5	4					5	30	90	150	240	8	44	
6.0	4					5	40	100	150	300	10	4	
6.5	4					5	45	100	180	360	11	39	
7.0	3					5	5	60	120	180	*600	16	19
7.5	3					5	10	60	120	180	*660	17	24
8.0	3					5	15	60	120	210	*660	17	59

includes 8 hrs. sleeping time.

APPENDIX II

EDEL-KINDWALL CAISSON TABLE (AIR)
(AUTODEC III)

TIME ASCENT to 1st. hrs. stop	D E C O M P R E S S I O N											S T O P S			TOTAL TIME	
	40	36	32	28	24	20	16	12	8	4				hrs.	min	
0.5	9													0	9	
1.0	6							5	5	20				0	39	
1.5	6							5	20	60				1	34	
2.0	5						5	10	40	120				3	4	
2.5	5						5	20	60	150				4	4	
3.0	5						5	40	80	180				5	14	
3.5	5						10	60	100	180				5	59	
4.0	4					5	15	70	120	210				7	9	
4.5	4					5	30	80	120	240				8	4	
5.0	4					5	40	90	150	240				8	54	
5.5	4					5	45	100	150	300				10	9	
6.0	3				5	5	60	120	150	360				11	49	
6.5	3				5	10	70	120	180	*600				16	34	
7.0	3				5	15	70	120	210	*660				18	9	
7.5	3				5	20	80	120	240	*660				18	54	
8.0	2			5	5	20	90	120	240	*660				19	9	
2.5	8									10				0	19	
1.0	7							5	10	25				0	50	
1.5	6						5	5	20	80				2	0	
2.0	6						5	15	60	120				3	30	
2.5	6						5	30	70	150				4	25	
3.0	5					5	10	45	100	180				5	50	
3.5	5					5	20	60	120	210				7	5	
4.0	5					5	30	70	120	240				7	55	
4.5	5					5	50	90	150	240				9	5	
5.0	5					5	60	100	150	300				10	25	
5.5	4				5	10	60	120	180	300				11	25	
6.0	4				5	15	70	120	180	360				12	40	
6.5	4				5	20	90	120	240	*600				18	5	
7.0	3			5	5	30	100	120	240	*660				19	30	
7.5	3			5	10	30	120	120	240	*660				19	55	
8.0	3			5	15	40	120	120	300	*660				21	10	

s 8 hrs. sleeping time.

APPENDIX II

DEL-KINDWALL CAISSON TABLE (AIR)
(AUTODEC III)

ASCENT (to 1st. stop)	D E C O M P R E S S I O N											S T O P S		TOTAL TIME	
	40	36	32	28	24	20	16	12	8	4			hrs.	min.	
8									5	10			0	25	
7								5	10	30			0	55	
6							5	10	30	80			2	15	
6							5	20	60	120			3	35	
5						5	10	40	80	150			4	55	
5						5	20	60	120	180			6	35	
5						5	30	70	120	210			7	25	
5						5	45	90	150	240			9	0	
4					5	10	60	90	150	300			10	25	
4					5	20	60	120	150	300			11	5	
4					5	30	80	120	180	360			13	5	
3				5	5	40	80	120	210	*600			17	50	
3				5	10	40	90	120	240	*660			19	35	
3				5	15	45	90	150	240	*660			20	15	
3				5	20	45	100	150	240	*720			21	30	
2			5	5	30	60	120	150	300	*720			23	20	
9									5	15			0	31	
7							5	5	10	40			1	11	
6						5	5	10	30	90			2	31	
6						5	5	30	60	150			4	21	
6						5	15	40	100	150			5	21	
6						5	30	60	120	180			6	46	
6						10	40	80	120	240			8	21	
5					5	15	60	90	150	240			9	31	
5					5	30	60	100	150	300			10	56	
5					5	40	80	120	180	360			13	16	
4				5	5	40	90	120	180	*600			17	31	
4				5	5	50	90	120	240	*660			19	41	
4				5	10	60	90	150	240	*660			20	26	
3			5	5	15	60	100	150	300	*660			21	46	
3			5	5	20	70	120	150		*720			23	21	
3			5	5	30	70	120	180	*540	480			24	1	

8 hrs. sleeping time..

APPENDIX II

EDEL-KINDWALL CAISSON TABLE (AIR)
(AUTODEC III)

DEPTH psi	TIME ASCENT to 1st. hrs.	ASCENT stop	D E C O M P R E S S I O N										TOTAL TIME		
			40	36	32	28	24	20	16	12	8	4	hrs.	min.	
44	0.5	8									5	5	15	0	36
44	1.0	7								5	10	15	45	1	26
44	1.5	6							5	10	10	40	120	3	16
44	2.0	6							5	10	40	60	150	4	36
44	2.5	6							5	30	40	120	150	5	56
44	3.0	5						5	10	40	60	120	210	7	36
44	3.5	5						5	15	45	90	150	240	9	16
44	4.0	5						5	30	60	90	150	300	10	46
44	4.5	4				5		10	30	80	120	150	360	12	46
44	5.0	4				5		10	40	90	120	180	*600	17	36
44	5.5	4				5		10	50	90	120	210	*660	19	16
44	6.0	3			5	10		15	60	90	150	240	*660	20	41
44	6.5	3			5	10		15	80	90	150	300	*660	22	1
44	7.0	3			5	10		20	80	120	150	300	*720	23	36
44	7.5	3			5	10		30	80	120	180	300	*720	24	16
44	8.0	2		5	10	15		30	80	120	210	*540	540	26	1
46	0.5	9									5	10	15	0	42
46	1.0	8								5	10	15	50	1	32
46	1.5	7							5	10	15	45	120	3	27
46	2.0	6						5	10	10	40	70	150	4	57
46	2.5	6						5	10	30	60	120	180	6	57
46	3.0	6						5	15	40	80	120	240	8	32
46	3.5	6						5	30	60	90	150	240	9	47
46	4.0	5				5		10	40	70	100	180	300	11	57
46	4.5	5				5		10	45	80	120	180	360	13	32
46	5.0	5				5		15	60	90	120	210	*600	18	32
46	5.5	4			5	10		20	70	90	150	240	*660	20	57
46	6.0	4			5	10		30	70	90	150	240	*720	22	7
46	6.5	4			5	10		30	80	100	180	300	*660	22	57
46	7.0	3		5	10	15		40	80	120	180	300	*720	24	42
46	7.5	3		5	10	15		40	80	120	210	*600	480	26	12
46	8.0	3		5	10	15		50	90	120	240	*600	480	27	2

*Includes 8 hrs. sleeping time.

APPENDIX II

EDEL-KINDWALL CAISSON TABLE (AIR)
(AUF DEC III)

TIME ASCENT (to 1st stop		D E C O M P R E S S I O N										S T O P S		TOTAL TIME	
hrs.	stop	40	36	32	28	24	20	16	12	8	4	hrs. min.			
0.5	8							5	5	10	15	0	47		
1.0	7						5	10	10	15	60	1	52		
1.5	6					5	10	15	15	60	120	3	57		
2.0	6					5	10	15	40	100	150	5	32		
2.5	6					5	15	40	60	120	180	7	12		
3.0	5				5	10	20	45	90	120	240	9	2		
3.5	5				5	10	40	60	90	150	240	10	7		
4.0	5				5	15	40	80	120	180	300	12	32		
4.5	4			5	5	15	60	80	120	180	360	13	57		
5.0	4			5	5	30	60	90	150	240	*660	20	52		
5.5	4			5	10	30	80	90	150	240	*720	22	17		
6.0	3		5	5	10	40	80	100	180	240	*720	23	12		
6.5	3		5	5	10	60	80	120	180	*540	480	24	52		
7.0	3		5	10	15	60	80	120	210	*540	540	26	32		
7.5	3		5	10	15	70	80	150	240	*540	540	27	42		
8.0	2	5	5	10	15	70	90	150	240	*600	540	28	57		
0.5	9							5	5	10	20	0	52		
1.0	8						5	10	10	20	70	2			
1.5	7					5	10	15	20	60	150	4	35		
2.0	7					5	10	30	50	120	150	6	18		
2.5	6				5	5	15	40	60	120	210	7	48		
3.0	6				5	10	30	60	90	150	240	9	58		
3.5	6				5	15	40	70	100	150	300	11	33		
4.0	5			5	5	20	50	80	120	180	360	13	53		
4.5	5			5	5	30	60	90	120	210	*600	18	53		
5.0	5			5	5	40	70	90	150	240	*660	21	13		
5.5	4		5	5	10	45	80	100	150	300	*660	22	48		
6.0	4		5	5	15	60	80	120	180	*540	480	24	58		
6.5	4		5	5	20	70	80	120	180	*540	540	26	13		
7.0	3	5	5	10	20	70	90	120	240	*600	480	27	33		
7.5	3	5	5	10	30	70	90	150	240	*600	540	29	13		
8.0	3	5	5	10	40	70	120	150	*480	360	540	29	53		

Includes 2 hrs. sleeping time.

APPENDIX III

CAISSON TABLE AUTODEC II (AIR)

(These tables failed on test producing a positive bone scan and clinical bends)

DEPTH psi	TOB hrs.	ASCENT TO 1st. stop	(D E C O M P R E S S I O N S T O P S)								TOTAL TIME		
			36	32	28	24	20	16	12	8	4	hrs.	min.
14	5.5	4										0	4
14	6.0	3								5		0	9
14	6.5	3								10		0	14
14	7.0	3								15		0	19
14	7.5	3								20		0	24
14	8.0	3								30		0	34
16	5.0	3								13		0	17
16	5.5	3								21		0	25
16	6.0	3								29		0	33
16	6.5	3								37		0	41
16	7.0	2							5	40		0	49
16	7.5	2							5	48		0	57
16	8.0	2							5	56		1	5
18	3.5	4								9		0	14
18	4.0	4								12		0	17
18	4.5	4								28		0	33
18	5.0	3							5	38		0	48
18	5.5	3							5	46		0	56
18	6.0	3							5	53		1	3
18	6.5	3							5	61		1	11
18	7.0	3							5	69		1	19
18	7.5	3							5	77		1	27
18	8.0	3							5	85		1	35
20	1.5	5										0	5
20	2.0	4								10		0	15
20	2.5	4								14		0	19
20	3.0	3							5	18		0	28
20	3.5	3							5	28		0	38
20	4.0	3							5	33		0	43
20	4.5	3							5	43		0	53
20	5.0	3							5	53		1	3
20	5.5	3							5	58		1	8
20	6.0	3							5	63		1	13
20	6.5	3							10	67		1	22
20	7.0	3							15	70		1	30
20	7.5	3							20	80		1	45
20	8.0	3							30	100		2	15

APPENDIX III

CAISSON TABLE AUTODEC II (AIR)

(These tables failed on test producing a positive bone scan and clinical bends)

TOB hrs.	ASCENT TO 1st stop	(D E C O M P R E S S I O N S T O P S)								TOTAL TIME		
		36	32	28	24	20	16	12	8	4	hrs.	min.
1.5	5									10	0	16
2.0	5									18	0	24
2.5	4								5	20	0	31
3.0	4								5	27	0	38
3.5	4								5	42	0	53
4.0	4								5	57	1	8
4.5	4								10	65	1	21
5.0	4								10	77	1	33
5.5	4								15	84	1	45
6.0	4								20	90	1	56
6.5	4								30	120	2	36
7.0	4								40	120	2	46
7.5	4								50	150	3	26
8.0	4								60	180	4	6
1.0	0										0	6
1.5	5									17	0	23
2.0	4								5	16	0	27
2.5	4								5	29	0	40
3.0	4								5	41	0	52
3.5	4								10	56	1	12
4.0	4								20	66	1	32
4.5	4								20	79	1	45
5.0	4								25	86	1	57
5.5	4								30	106	2	22
6.0	4								40	120	2	46
6.5	4								50	150	3	26
7.0	4								60	180	4	6
7.5	3							15	60	180	4	21
8.0	3							30	60	240	5	36

Does it state limit of standard workshift.

APPENDIX III

CAISSON TABLE AUTODEC II (AIR)

(These tables failed on test producing a positive bone scan and clinical bends)

TIME	TOB hrs.	ASCENT TO 1st stop	(D E C O M P R E S S I O N S T O P S)									TOTAL TIME		
			36	32	28	24	20	16	12	8	4	hrs.	min.	
	1.0	7											0	7
	1.5	5								5	17		0	29
	2.0	5								5	22		0	34
	2.5	5								10	39		0	56
	3.0	5								15	47		1	9
	3.5	5								15	65		1	27
	4.0	5								20	77		1	44
	4.5	5								30	86		2	3
	5.0	4							5	30	100		2	22
	5.5	4							10	30	120		2	47
	6.0	4							15	40	150		3	32
	6.5	4							20	50	180		4	17
	7.0	4							30	60	240		5	37
	7.5	4							45	60	240		5	52
	8.0	4							60	60	300		7	7
	0.5	7											0	7
	1.0	6									16		0	23
	1.5	5								5	19		0	31
	2.0	5								5	29		0	41
	2.5	5								10	53		1	10
	3.0	5								15	76		1	38
	3.5	5								20	85		1	52
	4.0	5								30	90		2	7
	4.5	4							5	30	120		2	42
	5.0	4							10	40	150		3	27
	5.5	4							15	45	180		4	7
	6.0	4							20	60	210		4	57
	6.5	4							30	70	240		5	47
	7.0	4							45	90	300		7	22
	7.5	3						15	60	90	360		8	52
	8.0	3							60	90	360		9	7

15 indicate limit of standard workshift.

APPENDIX III

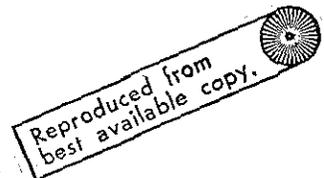
CAISSON TABLE AUTODEC II (AIR)

(These tables failed on test producing a positive bone scan and clinical bends)

DEPTH ft.	TOE hrs.	ASCENT TO 1st stop	(D E C O M P R E S S I O N S T O P S)									TOTAL TIME		
			36	32	28	24	20	16	12	8	4	hrs.	min.	
0	0.5	8											0	8
0	1.0	6								5	15		0	28
0	1.5	6								5	25		0	38
0	2.0	5							5	10	39		1	2
0	2.5	5							5	20	51		1	24
0	3.0	5							5	30	62		1	45
0	3.5	5							10	40	99		2	7
0	4.0	5							10	40	90		2	28
0	4.5	5							15	45	120		3	8
<hr/>														
0	5.0	5							20	60	150		3	58
0	5.5	5							30	90	180		5	8
0	6.0	5							45	90	240		6	23
0	6.5	5							60	120	240		7	8
0	7.0	4						15	60	120	360		9	23
0	7.5	4						30	60	120	360		9	38
0	8.0	4						60	60	150	660*		15	38
<hr/>														
0	0.5	8											0	8
0	1.0	6								5	22		0	35
0	1.5	6								10	42		1	0
0	2.0	6								20	57		1	25
0	2.5	5							5	30	69		1	52
0	3.0	5							10	30	90		2	18
0	3.5	5							15	30	120		2	53
0	4.0	5							20	40	150		3	38
<hr/>														
0	4.5	5							30	60	180		4	38
0	5.0	5							5	30	70	210	5	23
0	5.5	5							10	30	90	240		18
0	6.0	4							15	45	100	300	7	48
0	6.5	4							20	60	120	360	9	28
0	7.0	4							30	60	150	420	11	8
0	7.5	3						15	30	60	180	660*	15	53
0	8.0	3						30	60	60	180	720*	17	38

* Includes eight hour sleeping cycle (total time on air)

Lines indicate limit of standard workshift.



APPENDIX III

CAISSON TABLE AUTODEC II (AIR)

(These tables failed on test producing a positive bone scan and clinical bends)

DEPTH si	TOB hrs.	ASCENT TO 1st stop	(D E C O M P R E S S I O N S T O P S)								TOTAL TIME		
			36	32	28	24	20	16	12	8	4	hrs.	mins
4	0.5	9										0	9
4	1.0	7							5	25		0	39
4	1.5	6						5	15	30		0	59
4	2.0	6						5	20	59		1	38
4	2.5	6						10	30	76		2	5
4	3.0	6						15	40	90		2	34
4	3.5	6						20	40	120		3	9
4	4.0	6						30	50	150		3	59
<hr/>													
	4.5	5						5	30	90	180	5	14
	5.0	5						10	40	90	240	6	29
	5.5	5						15	45	120	300	8	9
	6.0	5						20	60	150	360	9	59
	6.5	5						30	60	180	420	11	39
	7.0	4					15	30	60	240	660*	16	54
	7.5	4					30	30	70	240	660*	17	19
	8.0	4					60	60	60	240	720*	19	9
<hr/>													
	0.5	9										0	9
	1.0	7							10	25		0	44
	1.5	6						5	20	30		1	4
	2.0	6						10	30	64		1	53
	2.5	6						20	40	74		2	23
	3.0	6						30	45	90		2	54
	3.5	5					5	30	60	120		3	44
<hr/>													
	4.0	5					10	30	80	180		5	9
	4.5	5					15	30	90	240		6	24
	5.0	5					20	45	120	300		8	14
	5.5	5					30	60	150	360		10	9
	6.0	4				10	30	60	180	420		11	49
	6.5	4				20	30	70	240	660*		17	9
	7.0	4				30	45	80	240	660*		17	44
	7.5	3			15	30	60	80	300	660*		19	14
	8.0	3			30	60	60	100	300	660*		20	19

* Includes eight hour sleeping cycle (total time on air)

Lines indicate limit of standard workshift.

APPENDIX III

CAISSON TABLE AUTODEC II (AIR)

(These tables failed on test producing a positive bone scan and clinical bends)

DEPTH psi	TOB hrs.	ASCENT TO 1st stop	(D E C O M P R E S S I O N S T O P S)								TOTAL TIME		
			36	32	28	24	20	16	12	8	4	hrs.	mins
38	0.5	10										0	10
38	1.0	8								15	24	0	49
38	1.5	7							10	20	33	1	13
38	2.0	7							15	30	73	2	8
38	2.5	6						5	20	40	97	2	52
38	3.0	6						10	30	45	120	3	35
38	3.5	6						15	30	70	180	5	5
38	4.0	6						20	30	120	240	7	0
38	4.5	6						30	45	120	300	8	25
38	5.0	5					5	30	60	150	360	10	15
38	5.5	5					10	30	70	180	420	12	0
38	6.0	5					20	30	90	240	660*	17	30
38	6.5	5					30	30	120	240	660*	18	10
38	7.0	4				15	30	60	120	240	660*	18	55
38	7.5	4				30	30	60	120	300	660*	20	10
38	8.0	4				60	60	60	120	360	720*	23	10
40	0.5	9									5	0	15
40	1.0	7							5	15	20	0	50
40	1.5	7							15	20	39	1	24
40	2.0	6						5	15	40	73	2	23
40	2.5	6						10	30	45	90	3	5
40	3.0	6						15	30	60	120	3	55
40	3.5	6						20	40	90	180	5	40
40	4.0	6						30	45	120	240	7	25
40	4.5	5					10	30	60	150	360	10	20
40	5.0	5					20	30	70	180	420	12	10
40	5.5	5					30	30	90	240	660*	17	40
40	6.0	4				10	30	30	120	240	660*	18	20
40	6.5	4				20	30	30	150	240	660*	19	0
40	7.0	4				30	30	60	150	240	720*	20	
40	7.5	3			15	30	30	60	180	300	720*	22	25
40	8.0	3			30	60	60	60	180	600*	480	24	40

* Includes eight hour sleeping cycle (total time on air)

APPENDIX III

CAISSON TABLE AUTODEC II (AIR)

(These tables failed on test producing a positive bone scan and clinical bends)

PTH i	TOB hrs.	ASCENT TO 1st stop	(D E C O M P K E S S I O N S T O P S)								TOTAL TIME		
			36	32	28	24	20	16	12	8	4	hrs.	min.
	0.5	10									10	0	21
	1.0	8							10	15	20	0	56
	1.5	7						5	15	20	51	1	42
	2.0	7						10	15	30	78	2	24
	2.5	7						20	30	45	90	3	16
	3.0	7						30	30	70	150	4	51
	3.5	6						5	30	40	90	6	56
	4.0	6						10	30	60	120	7	51
	4.5	6						20	30	90	150	11	1
	5.0	6						30	30	90	180	16	41
	5.5	5				10		30	45	120	240	18	36
	6.0	5				20		30	60	120	240	19	1
	6.5	5				30		30	60	150	300	20	41
	7.0	4			15	30		30	70	180	300	22	36
	7.5	4			30	30		30	90	180	360	24	11
	8.0	4			60	60		60	90	180	600*	25	41
	0.5	9								5	10	0	26
	1.0	8							15	15	23	1	4
	1.5	7						10	15	30	52	1	58
	2.0	7						15	15	45	68	2	34
	2.5	6						5	20	30	60	4	6
	3.0	6						10	30	45	90	6	6
	3.5	6						20	30	60	120	8	1
	4.0	6						30	30	60	150	9	41
	4.5	5				10		30	30	90	180	16	51
	5.0	5				20		30	40	120	240	18	41
	5.5	5				30		30	45	150	240	19	26
	6.0	4			10	30		30	60	150	300	20	51
	6.5	4			20	30		30	70	180	300	22	41
	7.0	4			30	30		30	90	180	360	24	11
	7.5	3			15	30		30	60	240	600*	25	56
	8.0	3			30	60		60	90	240	600*	27	11

Lines indicate limit of standard workshift.

* Includes eight hour sleeping cycle (total time on air)

APPENDIX III

CAISSON TABLE AUTODEC II (AIR)

(These tables failed on test producing a positive bone scan and clinical bends)

DEPTH psi	TOB hrs.	ASCENT TO 1st stop	(D E C O M P R E S S I O N S T O P S)										TOTAL TIME		
			36	32	28	24	20	16	12	8	4	hrs.	min		
46	0.5	10										10	10	0	32
46	1.0	8							5	15	15	30	30	1	17
46	1.5	8							15	15	30	67	67	2	19
46	2.0	7						5	15	20	45	90	90	3	7
46	2.5	7						10	20	40	60	120	120	4	22
46	3.0	7						20	30	45	90	180	180	6	17
46	3.5	7						30	30	60	120	240	240	8	12
46	4.0	6				10		30	30	70	150	360	360	11	2
46	4.5	6				20		30	40	90	180	660*	660*	17	12
46	5.0	6				30		30	45	120	240	660*	660*	18	57
46	5.5	5			10	30		30	60	150	240	720*	720*	20	52
46	6.0	5			20	30		30	90	180	300	720*	720*	23	2
46	6.5	5			30	30		30	120	180	360	720*	720*	24	42
46	7.0	4		15	30	30		45	120	240	600*	480	480	26	12
46	7.5	4		30	30	30		60	120	240	600*	480	480	26	42
46	8.0	4		60	60	60		60	120	240	600*	480	480	28	12
48	0.5	9								5	10	10	10	0	37
48	1.0	8							10	15	15	30	30	1	22
48	1.5	7						10	15	15	30	62	62	2	24
48	2.0	7						20	20	30	60	120	120	4	22
48	2.5	7						30	30	45	90	180	180	6	27
48	3.0	6				10		30	30	60	120	240	240	8	22
48	3.5	6				20		30	30	60	150	300	300	10	2
48	4.0	6				30		30	40	90	180	420	420	13	22
48	4.5	5			10	30		30	45	120	180	720*	720*	19	7
48	5.0	5			20	30		30	60	150	240	720*	720*	21	2
48	5.5	5			30	30		30	70	180	300	720*	720*	22	52
48	6.0	4		10	30	30		30	90	180	360	720*	720*	24	22
48	6.5	4		20	30	30		45	120	240	540*	480	480	25	17
48	7.0	4		30	30	30		60	120	240	600*	480	480	26	42
48	7.5	3	15	30	30	30		60	150	240	600*	480	480	27	27
48	8.0	3	30	60	60	60		60	150	540*	420	420	420	31	12

Lines indicate limit of standard workshift.

... hour sleeping cycle (total time on air)

APPENDIX III

CAISSON TABLE AUTODEC II (AIR)

(These tables failed on test producing a positive bone scan and clinical bends)

DEPTH psi	TOB hrs.	ASCENT TO 1st stop	(D E C O M P R E S S I O N S T O P S)								TOTAL TIME hrs. min		
			36	32	28	24	20	16	12	8	4		
50	0.5	10							10	10	10	0	43
50	1.0	9						15	15	15	30	1	28
50	1.5	8					20	20	20	30	61	2	44
50	2.0	8					30	30	30	60	120	4	43
50	2.5	7				10	30	30	45	90	180	6	38
50	3.0	7				20	30	30	60	120	240	8	33
50	3.5	7				30	30	30	70	150	360	11	23
50	4.0	6			10	30	30	40	90	180	420	13	33
50	4.5	6			20	30	30	60	120	240	720*	20	33
50	5.0	6			30	30	30	70	150	300	720*	22	23
50	5.5	5		10	30	30	30	90	180	360	720*	24	23
50	6.0	5		20	30	30	40	120	180	360	720*	25	13
50	6.5	5		30	30	30	60	120	240	600*	480	26	43
50	7.0	4	15	30	30	30	60	150	240	600*	480	27	28
50	7.5	4	30	30	30	40	60	180	540*	420	480	30	23
50	8.0	4	60	60	60	60	60	180	540*	420	480	32	13

Lines indicate limit of standard workshift.

*Includes eight hour sleeping cycle (total time on air)

TABLE 12-5 - STANDARD DECOMPRESSION
SCHEDULES FOLLOWING NORMOXIC NITROGEN-OXYGEN
SATURATION EXPOSURES
FROM: THE NOAA DIVING MANUAL

MAY BE USED SAFELY WITH AIR SATURATION
FROM 60 FSW

For use when accident or incident requires emergency
use of tables from saturation exposure.

Decompression Using Air and Oxygen
Saturation From 0 to 100 FSW at 5 FSW Intervals

Saturation Depth (FSW)	Range	First Stop			Subsequent Stops			Time At Stop (HR: MIN)
		Depth (FSW)	Gas	Time At Stop (HR: MIN)	Depth (FSW)	Gas	Time At Stop (HR: MIN)	
96-100		80	Air	3:00	75	Air	4:00	
91-95		75	Air	3:00	70	Air	4:00	
86-90		70	Air	3:00	65	Air	4:30	
81-85		65	Air	3:00	60	Air	4:30	
76-80		60	Air	3:00	55	Air	5:00	
71-75		55	Air	3:30	50	Air	5:00	
66-70		50	Air	3:30	45	Air	5:00	
61-65		45	Air	3:30	40	Air	5:00	
56-60		40	Air	4:00	35	Air	0:30	
51-55		35	Oxygen	1:00	35	Oxygen	1:00	
					35	Air	0:30	
					35	Oxygen	1:00	
46-50		30	Air	2:00	30	Air	2:00	
					30	Oxygen	1:00	
41-45		25	Oxygen	0:30	25	Air	0:30	
					25	Oxygen	1:00	
36-40		20	Air	1:30	20	Air	3:00	
					20	Oxygen	1:00	
31-35		15	Oxygen	1:00	15	Air	0:30	
					15	Oxygen	1:00	
26-30		10	Air	2:00	10	Air	4:00	
					10	Oxygen	1:00	
22-25		5	Oxygen	0:30	5	Air	0:30	
					5	Oxygen	1:00	
					5	Air	0:30	
					5	Oxygen	1:00	
					30	Oxygen	0:30	

APPENDIX V

PROPOSED SUPPLEMENTARY RULES

FOR THE USE OF OXYGEN DURING

DECOMPRESSION OF COMPRESSED AIR TUNNEL WORKERS

I. Physical Plant and Equipment

- A. Tight fitting, double-seal oro-nasal masks equipped with a discharge hose to exhaust exhaled oxygen from the decompression lock shall be provided. This type of mask and its associated valves and piping are collectively termed an "overboard dump system". When a work-shift consists of ten men or less, at least two extra masks shall be placed in the decompression lock. If more than ten men are decompressing at a time, four extra masks shall be placed in the lock. These masks need not be connected when not in use. All masks shall be equipped with a demand regulator on the inlet side and a vacuum regulator on the discharge side. The vacuum regulator shall be capable of handling pressure differentials from the interior of the lock to the outside of up to 26 psig. A second vacuum reducer may be interposed in the discharge manifold as it leaves the chamber to accomplish this if necessary.
- B. Oxygen shall be supplied to a manifold in the decompression lock into which the masks can be plugged using quick disconnect fittings. This manifold shall be oxygen cleaned at the time of installation and shall be of copper with silver soldered couplings.
- C. An oxygen regulator installed inside the lock of sufficient size to supply oxygen to the number of men decompressing shall regulate the admission of oxygen to the manifold at a pressure of 50 lbs. greater than chamber pressure.
- D. The oxygen supply can be from high pressure oxygen cylinders connected to a manifold with a reducer valve fitted to the high pressure manifold discharge set at 150 lbs. The oxygen cylinders and manifold may be situated in the tunnel in a protected area or topside. In any case, the lock tender must be quickly able to visually verify the cylinder pressures. Alternatively, a cryogenic or liquid oxygen source of adequate size may be used having a vaporization pressure set at 150 psig.
- E. The available oxygen supply at the beginning of any decompression shall be equal to 150% of anticipated requirement. Minimum requirements can be calculated on the basis that each H cylinder contains 220 cu. ft. of usable oxygen at a starting pressure of 2,250 psi. It is anticipated that the average man will consume approximately 0.5 cu ft. per minute at atmospheric pressure. Decompression, however, will be carried out at greater than normal atmospheric pressure so the final result will have to be multiplied by the number of atmospheres absolute or fractions thereof which the crew experiences during decompression.

POUNDS PER SQUARE INCH GAUGE (PSIG)
EXPRESSED IN ATMOSPHERES ABSOLUTE

4 lbs.	= 1.27 atmospheres
8 lbs.	= 1.54 atmospheres
12 lbs.	= 1.82 atmospheres
16 lbs.	= 2.09 atmospheres
20 lbs.	= 2.36 atmospheres

An example of the calculation for the minimum oxygen requirement is given below:

Assume that a tunnel crew of six men is decompressing on the oxygen table from six hours exposure at 24 psig. The decompression requires a five minute stop on air at 12 psig, a thirty minute stop on oxygen at 8 psig, then five minutes of air at 4 psig followed by sixty minutes of oxygen at 4 psig. No oxygen is required at 12 psig, but thirty minutes and sixty minutes of oxygen are required at 8 and 4 psig respectively. As seen from the table, 8 psig is equal to 1.54 atmospheres and 4 psig is equal to 1.27 atmospheres.

Calculations are made as follows:

$$\begin{aligned} 6 \text{ men} \times 0.5 \text{ ft}^3/\text{min.} \times 30 \text{ min.} \times 1.54 \text{ atmospheres absolute} &= 138.6 \text{ ft}^3 \\ 6 \text{ men} \times 0.5 \text{ ft}^3/\text{min.} \times 60 \text{ min.} \times 1.27 \text{ atmospheres absolute} &= \frac{228.6 \text{ ft}^3}{367.2 \text{ ft}^3} \\ 367.2 \text{ ft}^3 \times 150\% &= 550.8 \text{ ft}^3 \\ 550.8 \text{ ft}^3 - 220 \text{ ft}^3 \text{ usable O}_2 \text{ per cylinder} &= 2.5 \text{ cylinders.} \end{aligned}$$

Therefore one must start decompression with a minimum of 3 full oxygen cylinders available.

- F. The discharge line which carries the exhaust oxygen, which has been breathed, is carried topside and discharged to the atmosphere. It shall be carried high enough so that cigarette butts, etc. cannot be inadvertently dropped into it, and topped with a U fitting or rain shield.
- G. An oxygen meter shall be installed with its sensing element in a pipe discharging air from the decompression lock. This shall be a pipe separate from the oxygen overboard dump discharge. The oxygen meter shall be equipped with a visible and audible alarm set to go off when the oxygen level in the air discharge pipe measured at atmospheric pressure external to the lock reaches 23%.
- H. All lights in the decompression lock shall have the bulbs enclosed by pressure proof glass shields and wiring shall be carried in conduit.
- I. A fire hose or hoses shall be installed which can reach any part of the decompression lock. Hoses shall be rot proof, be equipped with a fog nozzle and be connected to a wet standpipe. A 1/4 turn ball valve shall activate the hose(s). Water pressure shall be at least 50 psi greater than any anticipated pressure in the lock.

II. Operating Procedures When Using Oxygen Decompression

- A. Before the crew enters the lock, the lock tender will pressurize the lock with compressed air and calibrate the oxygen meter attached to the exhaust line externally to 21% ensuring there is flow through the exhaust lines at the time of calibration.
- B. A responsible foreman shall be present in the lock at all times when oxygen is breathed during decompression.
- C. There will be absolutely no smoking material taken into the compressed air tunnel at any time and there will be absolutely no smoking at any time during decompression in the lock.
- D. Signs will be conspicuously posted at both ends of the decompression lock strictly forbidding any smoking, carrying or producing any fire or open flame.
- E. When oxygen masks are applied, they shall be applied simultaneously by all workers and the lock tender shall not start recording oxygen decompression time until all of the workers have started to breathe oxygen.
- F. The demand regulators on the masks shall be adjusted so as not to produce a free flow of oxygen at any time. The foreman shall verify this.
- G. When the oxygen masks are removed, the foreman shall verify that no masks are free flowing after they have been removed. He shall instruct the men to carefully monitor this also.
- H. Should an oxygen mask fail for any reason, one of the spare masks is to be substituted. The time required for the substitution of the mask on any given worker shall be added to the total oxygen time for that stop.
- I. The lock tender shall continuously ventilate the lock so as to maintain the oxygen content of the discharge air below 23%. If the high oxygen alarm goes off indicating a percentage greater than 23%, he shall immediately increase the ventilation rate to bring the oxygen content of the low below 23%. He shall also immediately notify the foreman so that he may search for an oxygen leak from either a mask or piping.
- J. Men who are breathing oxygen are to remain at rest and are not to do exercise of any kind. They shall be suitably dressed to avoid chilling.
- K. The foreman shall carry a portable hand held oxygen meter in the lock and shall calibrate it properly at lock pressure before oxygen breathing is commenced. Alternatively, the lock tender may calibrate it to 21% outside the lock at normal atmospheric pressure and then place the meter in the lock before pressurizing it. The oxygen level in the air in the pressurized lock will read higher than normal even when no additional oxygen is present.

The table below indicates the calibration settings for the portable

oxygen meter in normal compressed air at various pressures.

<u>PSIG</u>	<u>Calibration Setting at Pressure</u>	<u>Maximum Permissible When O₂ in Use</u>	<u>Atmospheres Absolute</u>
20	49.6%	54.3%	2.36
18	46.6%	51.1%	2.22
16	43.9%	48.1%	2.09
14	41.0%	44.9%	1.95
12	38.2%	41.9%	1.82
10	35.3%	38.6%	1.68
8	32.3%	35.4%	1.54
6	29.6%	32.4%	1.41
4	26.7%	29.2%	1.27

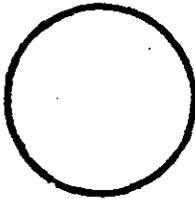
The oxygen level will read higher in the lock under pressure because the oxygen molecules are packed closer together. The oxygen meter probe in the exhaust line outside the chamber will read normally as the air has already been decompressed to normal pressure before it contacts the probe.

While in the lock, the foreman should check his portable meter occasionally at various sites among the decompressing crew to detect any leaks in the oxygen breathing equipment early.

This table is to be posted prominently in the decompression lock for the foreman's use

- L. In the very remote possibility that anyone should experience an oxygen reaction (seizure) the foreman should immediately remove the man's oxygen mask and assure that he has an airway by turning his head back and pulling up on his chin. When the seizure is over, he may be turned on his side, but again maintaining the airway. The physician shall be notified immediately.
- M. Decompression following an oxygen reaction or if any worker for any reason cannot breathe oxygen, shall be in strict accordance with instructions from the retained physician. If the physician cannot be located, decompression from the point where oxygen breathing was interrupted shall be continued on the air decompression table repeating the stop where the oxygen reaction occurred.
- N. The lock tender shall carefully record all oxygen breathing periods as well as the total length of the decompression stop and shall notify the foreman when oxygen masks are to be donned and doffed.
- O. At the conclusion of decompression, all used oxygen masks are to be removed from the regulators, and washed in a suitable antiseptic solution which is not injurious to rubber.
- P. Full beards or beards which interfere in any way with a tight seal of the oxygen mask shall not be permitted. Mustaches are permitted.
- Q. Vaseline and other greases may not be used to insure a seal of the mask over beards.

- R. The foreman shall instruct all of the workmen regarding the hazards of fire when oxygen breathing procedures are disregarded.
- S. The lock tender shall insure that clean, dry masks are available to each shift before they start decompression and that the extra masks are available in the lock.
- T. The lock tender at the conclusion of each shift shall check the pressure of the oxygen cylinders and ascertain that enough oxygen is ready for decompression of the next shift.
- U. If for any reason oxygen breathing during decompression cannot be carried out according to the exact schedule, the retained physician shall be notified immediately.
- V. The lock tender shall insure that the decompression lock is maintained conspicuously clean with no unnecessary combustibles present in the lock.
- W. Before each shift decompresses, the lock tender shall check the fire hose valves to verify that fire-fighting water is available in the lock.
- X. In the event of fire, the lock tender shall immediately shut off the oxygen. If the fire is serious and not immediately controlled, the lock tender shall decompress the lock to the surface at once so that the crew can escape. When the lock is on the surface, the crew shall be immediately transferred to the medical lock on the surface, and the medical lock taken to 60 feet (26.7 psi). The surface interval shall not exceed 5 minutes if humanly possible to accomplish this. The physician is to be notified as soon as the men are evacuated.



THE KASSOUF COMPANY

THE MURRAY HILL CONSTRUCTION COMPANY

7738 COMMERCE PARK OVAL • CLEVELAND, OHIO 44131

(216) 524-4348

July 15, 1982

Eric P. Kindwall, M.D.
2900 West Oklahoma Ave.
Milwaukee, WI 53215

Dear Sir:

We have reviewed your proposed supplementary rules for the use of oxygen decompression for air tunnel workers. We are in agreement in general with your proposed rules, however, there are a few exceptions.

It is our theory that the safe use of oxygen is a three-prong attack:
1.) instruction as to proper use, 2.) preventing oxygen build-up, and
3.) limiting ignition sources and flammable materials.

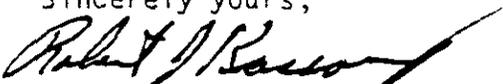
To that end, we advocate primary and back-up continuous monitoring of oxygen build-up within the lock. Back-ups on the oxygen supply system at points of possible failure, continuous ventilation of sufficient quantity, and backup methods and firefighting procedures should all else fail.

No set of rules can be all-encompassing. In large part, the safe implementation of oxygen decompression will rely on the dedication and intelligence of the people setting it up and using it. For this reason, we resist the formulation of specific procedures which may be contrary to the particular circumstances of a given project. We take particular exception to your Section II, Item V, wherein it is possible when following the rules in this case one may be forced in fact to act contrary to common sense. We suggest that this is covered in evacuation procedures under existing OSHA regulations and no additional rules are required.

We have added a few minor modifications to Sections B, C, F, H, and I (Section I) and Sections H and V (Section II).

Please be advised we expect to be under air on a one shift basis for some preliminary operations on or about the 26th of July.

We look forward to your comments.

These changes were made. Sincerely yours,
E.P.K. 

APPENDIX VI

SAFETY RESPONSIBILITIES OF EMPLOYEES

I. Project Engineer

1. The project engineer carries the ultimate responsibility for the safety of the entire project.
2. He is to monitor the activities of the safety engineer and the shift foremen to insure that these individuals are carrying out their responsibilities and that all relevant safety codes and practices are being observed.
3. Should an unsafe condition appear, the project engineer has the responsibility to halt further work, if necessary for human safety, until the condition can be rectified.
4. He shall be familiar with all applicable OSHA codes.

II. Project Safety Engineer

1. This individual is in immediate operational charge of all safety aspects of the job and is to make daily, or weekly inspections, as appropriate, of the working face, tunnel proper, the combination lock, the decompression locks, the medical locks, gas analysis equipment, tools and equipment, both in the tunnel and topside, and all pertinent records and logs to assure their being up to date.
2. A check list is provided to the safety engineer as an aid to inspections, but his responsibility extends to all safety aspects of the project whether or not they are noted on the check list.
3. The engineer shall do the necessary calculations for oxygen requirements (when oxygen decompression is used) and deliver these in writing to the lock tender. He shall also ensure that each foreman understands the maximum permissible oxygen levels permitted on the portable oxygen monitor at each decompression stop when oxygen is used.
4. He shall be familiar with all applicable OSHA codes.

III. Shift Foreman

1. Each shift foreman shall be responsible for the safe conduct of the work carried out during his shift.
2. At times of shift changeover, he shall be jointly responsible with the incoming shift foreman for an orderly and safe change of shift.
3. He shall ascertain that the proper decompression schedule is used for every member of the shift.

4. He shall bring to the attention of the project safety engineer any discrepancies in equipment and shall immediately rectify any equipment or procedural deficiencies.
5. He has authority to suspend work immediately if a situation develops which may endanger the welfare or safety of any workman.
6. The foreman shall be responsible for sampling the air on his shift if directed to do so by the project safety engineer.
7. He is responsible to see to it that the results of air sampling are entered in the proper log.
8. If oxygen decompression is used, he shall supervise the use of the oxygen masks and monitor the oxygen level in the decompression lock with a portable O₂ meter.
9. He should be familiar with the safety check list used by the project safety engineer.
10. In the event of accident or injury to a workman on the shift, the shift foreman or a responsible person designated by him shall notify the retained physician promptly.
11. The shift foreman shall be familiar with all the provisions of the OSHA code pertaining to compressed air tunneling.

IV. Lock Tender

1. The lock tender shall be familiar with the operation of the combination lock and the decompression lock(s).
2. It shall be his responsibility to see to it that fresh recording graphs are placed on the recorders at the appropriate intervals.
3. He shall operate the combination lock during decompression in such a manner that the proper decompression schedule is adhered to.
4. He shall permit no person to enter the compressed air lock without being logged in and he shall enter in the log the departure time of each person entering. He shall record in the log the date and pressure to which the individual is exposed.
5. The lock tender shall not permit anyone to enter the compressed air heading if he has exited compressed air within the preceding 12 hours. In an emergency, re-entry into the compressed air heading may be permitted, but only with the knowledge of the hyperbaric physician.
6. The lock tender shall see to it that the logs are maintained legibly and are not allowed to deteriorate due to dirt or water damage.
7. He shall be responsible for delivering the completed logs and recording graphs to the safety engineer's office when completed.

8. He shall assure that there is adequate ventilation in the combination lock during decompression. He shall be familiar with the posted decompression schedules and shall decompress anyone leaving the working heading in strict accordance with these schedules.
9. If oxygen decompression is in use, he shall monitor the oxygen meter recording the oxygen levels in the vent line from the decompression lock and shall calibrate said meter appropriately.

V. Compressorman

1. The compressorman on each shift shall see to it that the pressure in the tunnel is maintained at all times at the level requested by the shift foreman.
2. He shall be capable and qualified to operate the emergency medical lock whenever required.
3. He shall start the emergency Diesel generators and actually couple them to the compressor motors at least once a week. These tests are to be dated and logged.
4. He shall insure that the air intakes to both the high and low air compressors are so positioned that exhaust fumes from Diesel or gasoline powered engines are not drawn into the intakes.
5. In the event of electrical power failure, he shall immediately notify the project engineer and the project safety engineer.
6. He shall be familiar with the current OSHA regulations as they refer to the compressor plant.

VI. Miners, Muckers, Electricians and All Others Who Enter the Tunnel Heading

1. They shall have read the instructions to compressed air tunnel workers, or have had these instructions read to them.
2. They shall indicate that they understand these instructions and shall have signed the instructions indicating understanding before entering the tunnel environment.
3. Every workman shall observe all relevant safety rules and report unsafe conditions immediately to the shift foreman.

APPENDIX VII

INSPECTION CHECK LIST FOR PROJECT SAFETY ENGINEER

1. Check all paperwork at least once a week for the following:
 - A. Pressure recording graphs for all shifts.
 - B. Gauge verification logs for recording graph and tunnel.
 - C. Shift logs for time of entry, decompression and pressure for individuals.
 - D. Currency of medical certificates.
 - E. Completeness of incident or accident reports.
 - F. Atmosphere sampling logs
2. Check conditions around intakes for both high and low air compressors to insure that Diesel or gasoline engines are not operating in the area (daily).
3. Check logs to be sure that Diesel generators have been test-started and actually coupled to the air compressors at least once a week.
4. Ascertain that check valves in air supply piping in tunnel both at the inside end of the manlock and at the tunnel face are functional (daily).
5. See to it that air is analyzed at the heading for CO₂, O₂, CO, oxides of nitrogen at least one time per shift. Log these results. If CO₂ builds up over 0.5% in the area of the heading, open more vent lines or extend the air delivery pipe closer to the heading. Check the function of the air analyzer equipment in the office before entering the tunnel. The verification of proper operation of this gear should be made in strict accordance with the manufacturer's instructions (Mine Safety Equipment or other).
6. Check for free hydraulic oil on the surface of water in the area of the heading and anywhere in the tunnel.
7. Verify by appropriate CO₂ readings that no dead air exists midway between the heading and the manlock (as required).
8. Verify that fire main is full of water as it extends to the heading and that the hoses are functional and rot-proof.
9. Be sure that all direct reading Bourdon Tube Gauges connected directly to the manlock and working tunnel are calibrated by a master gauge at least every 3 months.
10. Verify that the first aid kits in the manlock and the tunnel are complete and in good condition (weekly). Replace any deteriorated, damaged or missing items.
11. Check operations of all telephones (daily).

12. Be sure safety lamp for detection of methane is functioning properly (daily).
13. Check emergency lighting (weekly).
14. Check toilet facilities in tunnel for sanitation (daily).
15. Emphasize to employees that a man must stand by with a fire hose and remain there for at least one-half hour after completion of any cutting or burning in the tunnel (unless there are no combustible materials in the immediate area).
16. If oxygen decompression is used, verify oxygen supply to be adequate, O₂ meters to be functional, and oxygen masks to be performing properly (daily).

APPENDIX VIII

CHECK LIST FOR PHYSICIAN INSPECTIONS OF THE TUNNEL SITE

1. Physician visits should be made every week to ten days. When the physician arrives on the job site, he should contact the project safety engineer and together with him, physically carry out an inspection as described on the project safety engineer's check list.
2. The physician, additionally should concentrate on checking over the medical treatment lock, its oxygen supply and the status of the medical supplies.
3. When not in use, the inner lock of the medical treatment chamber should be held at a pressure of 74 pounds per square inch and the outer lock held at a pressure of 5 pounds per square inch. This insures that no one enters the medical lock without authorization and that it remains clean and uncontaminated. Seventy-four pounds pressure in the inner lock acts as an air reserve and would allow for immediate compression of an accident victim in the outer lock without the need for additional compressed air in the event of power failure or catastrophic accident to the compressed air system. This is done by equalizing the pressure between the inner lock and the outer lock.
4. When the physician arrives to inspect, the chamber should be decompressed and the physician should enter, after removing his shoes, to ascertain that the oxygen masks actually function, and that other supplies and equipment are in proper order. When the inspection is complete, the chamber should be recompressed, by the compressor man, in the physician's presence. At this time, the proper function of all the valves and gauges can be ascertained.
5. While in the chamber, the physician should be alert to odors in the air which would indicate air contamination. Oil filters in the line from the compressor to the medical lock (Lufer sponges, Deltech separators) should be checked for cleanliness and proper function.
6. The physician should ascertain that the safety valve, when it lifts, will reseal on its own and that the pop-off pressure is at least 10% higher than the maximum pressure to which the chamber will be taken. (If the valve lifts at 76 psig, the chamber should not be operated with personnel inside, to pressures greater than 68.4 psig) (153 fsw).
7. On leaving the job site, the physician should inform the project safety engineer or project engineer of any discrepancies and make a written record of them.

APPENDIX IX

SUGGESTED MEDICAL SUPPLIES

I. Inside Medical Lock

1. Ambu or Lerdahl resuscitation bag and mask with tubing and regulator to connect to oxygen outlet.
2. Afrin nasal spray
3. Flashlight
4. Reflex hammer
5. Blood pressure cuff (Aneroid) - to be left with valve open or tubing disconnected.
6. Stethoscope - two hose
7. One battery operated quartz clock
8. Four pairs of ear mufflers (noise protection)

II. Outside Medical Lock

1. 6 - "H" Cylinders oxygen on manifold
2. 2 - 1 liter plastic intravenous infusion bags containing D 5% and half normal saline.
3. 2 - 1 liter plastic intravenous infusion bags of Ringer's lactate
4. 4 Intravenous infusion sets
5. 1 liter aqueous Betadine solution
6. Package of individually wrapped skin swabs
7. Selection of angiocath and needles of various sizes
8. A selection of soft French urinary catheters (sterile)
9. Urinary catheter tray
10. A selection of airways
11. One thoracentesis set with one-way valve
12. Two boxes assorted band-aids
13. One roll tubular bandage with aluminum applicator stent (for finger injuries)
14. One oxygen analyzer with probe connected to chamber exhaust line.
15. Package of plastic styrofoam cups

III. Inside Combination or Decompression Lock (Tunnel):

1. 3 bottles Afrin nasal spray
2. 6 rolls cling bandage
3. 6 ABD pads
4. 1 package sterile 4 x 4's
5. One box assorted band-aids
6. One roll adhesive tape
7. One electric clock
8. One hand held oxygen analyzer if oxygen decompression is being used.

APPENDIX X

SAMPLE APPLICATION FOR VARIANCE

TO: Occupational Safety and Health Administration
Department of Labor
Washington, D.C.

FROM: Any Tunneling Company
Main Street
U.S.A.

SUBJECT: Automatic or Cam Controlled Decompression Controllers

This company has applied for a variance to use the NIOSH interim decompression tables for compressed air in tunnel workers on the tunnel project in question. As these interim tables use stage decompression and not continuous or linear decompression stages, the necessity of using automatic decompression controllers to regulate pressure in the decompression lock is obviated. Continuous recording graphs provide a permanent record of the actual decompression profile, as previously. If our application for variance to use the interim decompression tables supplanting the present OSHA tables for decompression of compressed air tunnel workers is granted, we hereby request that a variance be granted to eliminate the use of the automatic decompression controller. The only reason for the present requirement for automatic decompression controllers is that regulation of very small amounts of pressure change over long periods of time is manually difficult or impossible using the present OSHA code. Stage decompression, has historically been managed easily and successfully with manual control since the beginning of this century. It is our understanding that the developers of the interim decompression tables have specifically noted that the application of the new tables will obviate the need for this controller.

This request for variance is urgent as it is anticipated that compressed air operations will begin soon (or definite date) .

R E P O R T

TO

NATIONAL INSTITUTE FOR OCCUPATIONAL SAFETY AND HEALTH

ON

A STUDY TO DETERMINE THE FEASIBILITY
FOR
DEVELOPING INTERIM DECOMPRESSION SCHEDULES
FOR
TUNNEL WORKERS

FROM

UNDERSEA MEDICAL SOCIETY, INC.
9650 ROCKVILLE PIKE
BETHESDA, MARYLAND 20014

4 SEPTEMBER 1979

A STUDY TO DETERMINE THE FEASIBILITY FOR DEVELOPING INTERIM
DECOMPRESSION SCHEDULES FOR TUNNEL WORKERS

Report To
National Institute for Occupational Safety and Health
(Work Order No. 79-3851)

Prepared By
Undersea Medical Society, Inc.
9650 Rockville Pike
Bethesda, Maryland

The accompanying report is in response to Work Order No. 79-3851 dated 8/2/79, which stated:

Determine the feasibility for developing interim decompression schedules to replace the present federal schedules which have been shown to be dangerous to tunnel workers. The interim schedules should have the following specifications:

- 1) A maximum decompression sickness rate of 5% with non-serious classification.
- 2) A maximum dysbaric osteonecrosis rate of 4% with shaft lesions only.
- 3) A minimum tunnel or caisson depth of 112 ft.
- 4) Ten (10) copies of the final report shall be delivered to the Project Officer at the following address:

Dr. Alan Purdy
HEW Parklawn Bldg.
5600 Fishers Lane, Mail Stop 8-23
Rockville, MD 20857

This study was held at the Undersea Medical Society, Inc., 9650 Rockville Pike, Bethesda, Maryland, on 23 July, 1979, and was funded by the National Institute for Occupational Safety and Health.

The opinions, conclusions and recommendations contained in this report are not to be construed as official or necessarily reflecting the views of the National Institute for Occupational Safety and Health.

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Background

In the fall of 1977, NIOSH awarded a small grant to Dr. E. P. Kindwall of St. Luke's Hospital in Milwaukee, to carry out skeletal x-ray surveys and bone scans on a group of compressed air tunnelers who had used the current OSHA-enforced Federal decompression schedules, at pressures ranging up to 44 psi, on a tunnel contract that was completed in 1973. Previous experience with what are now the Federal schedules in Seattle, San Francisco (on the Bay Area Rapid Transit Project), and in Milwaukee, involving pressures up to 36 psi, had revealed no serious problems with dysbaric osteonecrosis. In fact, a survey carried out by Dr. Leon Sealey, Project Director for the Seattle tunneling contract, showed that of 83 men followed for nearly 10 years after decompression according to Federal decompression schedules, only 4 cases of shaft lesions could be identified. These shaft lesions were minor and caused no disability. For this reason, it was generally assumed that the current OSHA decompression schedules were safe.

However, an August 1978 interim report of a survey of Milwaukee compressed air workers who had used the OSHA tables at pressures greater than 36 psi demonstrated that 5 of 20 men had severe juxta-articular lesions. This represented a 25% incidence of disabling dysbaric osteonecrosis apparently as a consequence of using the OSHA-enforced decompression schedules. Kindwall felt that a new set of decompression schedules was essential to reduce the incidence of dysbaric osteonecrosis and the incidence of decompression sickness, which, although treatable, was a troublesome factor in compressed air construction. It was estimated that the production and testing of a whole new set of tables would take at least two to three years.

The August 1978 interim report came to the attention of Dr. Alan Purdy of NIOSH, who suggested that, since it would take such a long time to develop and publish tested tables, NIOSH should promulgate new interim tables which might immediately reduce decompression sickness, morbidity, and bone destruction among caisson workers.

This Workshop (see list of participants above) was convened to explore the feasibility and advisability of devising interim decompression schedules and promulgating them for immediate use, while other studies were being carried out to test the more definitive decompression tables. It was noted that the present OSHA tables, as well as all previous U.S. tunnel tables, had been put into use without prior testing in the laboratory.

Definition of Interim vs. Permanent Tables

At the outset, Mr. LaRocca of OSHA explained that at the present time, OSHA did not have evidence that the present OSHA tables were inadequate, and the Agency did not feel there was a need for further study in this area. For OSHA to become involved, it would have to have indications from NIOSH that further work was needed, and would have to be convinced by scientific facts. Even if interim tables were promulgated, bringing them into regulatory status would be an extremely slow process. However, if the new interim schedules were mentioned in the Current Intelligence Bulletin as being desirable for tunnel contractors, the tables could be used immediately by granting the contractor a variance from the OSHA procedures.

Interim tables were defined as decompression schedules generated using the best available data from commercial diving and other sources, and which could reasonably be expected to eliminate or at least greatly diminish dysbaric osteonecrosis problems as well as the incidence of decompression sickness. Mr. Peter Edel of New Orleans, who was attending the Workshop, has computer data banks that include this information, and he has offered to produce new interim schedules using data from 15 years' experience in commercial diving and with other projects, such as TEKTITE and Navy experience. Any tables derived would take into account both successful and unsuccessful decompression schedules, as documented in industrial use, and would fall within safe limits based on these criteria. Thus, the interim tables would not be "tested" before promulgation, but they would take into account the results of field testing of the same or similar exposures and decompression profiles over the past several years. In this sense, the interim tables would be substantially "pre-tested."

Earlier, Mr. Edel had been asked to produce new decompression schedules for tunnel workers as part of a long-term research project that would be carried out at St. Luke's Hospital and the Medical College of Wisconsin in Milwaukee. Kindwall had proposed that new decompression schedules could be developed with Edel's data, and that these preliminary tables could then be reevaluated in the laboratory using human nitrogen washout studies and ultrasonic bubble imaging of stationary bubbles in the subject's tissues. Assistance with the ultrasonic bubble imaging would be provided by Dr. Hewlett E. Melton of the Department of Pathology at the Medical College of Wisconsin, a specialist in this area. It was proposed that tissue bubble imaging using the present OSHA tables then be compared with Edel's schedules and the nitrogen washout results. Additionally, the tables would then be tested at the exposure extremes in certain pressure ranges, taking care to avoid distortion of the results through acclimatization of subjects on the

one hand, or nitrogen build-up in the worker's tissues during the work week on the other. It was estimated that this kind of project to develop permanent or tested tables would require at least three years. A grant proposal to do this had been submitted to NIOSH, but at this point, Dr. Purdy had suggested developing interim tables as a start. If a grant to carry out rigorous testing of the interim tables was made, the final study would determine if the interim tables could become the permanent tables.

The Need for New Tables

The group felt that the first order of business was documenting the need for new decompression tables. Kindwall noted the Milwaukee experience of severe cases of dysbaric osteonecrosis occurring on the present OSHA schedules, and said that since his interim report of August 1978, additional cases had been discovered. The final report to NIOSH, to appear in September 1979, will reflect the true incidence, but even the interim report has demonstrated the incidence to be formidable. Dr. Behnke noted that the San Francisco tunneling project produced an unacceptably high incidence of decompression sickness, and Kindwall stated that in Milwaukee, using an anonymous reporting system, up to 26% of the men on a work shift had been found to suffer from decompression sickness after leaving the job. Reference was made to a meeting held at Freeport, Grand Bahama on August 22, 1972, which was attended by Dr. Heinz Schreiner of Ocean Systems, Dr. Christian J. Lambertsen of the University of Pennsylvania, Dr. Behnke, Mr. Edel, and Dr. Kindwall. At that time, before aseptic necrosis had been recognized as a problem associated with the OSHA schedules, the group met to discuss and suggest possible changes to be made in the Federal Code for decompressing caisson workers. This concern developed because of the high incidence of bends encountered in California and Washington state, as well as in Milwaukee. At that time, Dr. Behnke stated that "we have information to the effect that the Washington state tables (i.e., current Federal tables), are inadequate in the prevention of decompression sickness, specifically in the Lake Tunnel Project in Seattle where, at a pressure level ranging from 30 to 34 psig, 3,000 man shifts were followed by 51 cases of bends. The incidence was 1.7%. This is seemingly not too high. However, in our experience in the BART project (Bay Area Rapid Transit), at a pressure level of 30 psig approximately, in 29 shifts there was an incidence of decompression sickness which was in the range of from 13 to 35%. At a given time we had as many as eight men under treatment. At a pressure of 36½ psig, 55 man shifts, there were 3 cases of bends -- the incidence was 5½%. I think we have enough evidence to indicate again that in the pressure range of 30 to 35 psig the tables are totally inadequate." Dr. Lambertsen agreed with Dr. Behnke that "a random repair of any decompression system was undesirable and will not work."

These observations prompted the Workshop group to examine the current OSHA decompression schedules to determine if the reason for these shortcomings might be discerned by visual inspection of the schedules.

Known Ambiguities, Irregularities and Deficiencies of the Present OSHA Schedules

It was pointed out that decompression on the present OSHA schedules calls for continuous reduction of pressure at two different rates up to 24 psi, three varying rates up to 39 psi, and four continuous stages at pressures over 40 psi. The most important thing, however, is that considerable amounts of time are spent in the last stage of each schedule, which occurs between 4 psi and the surface. Thus, after a 4-hour exposure at 36 psi, two hours and 10 minutes are spent in decompressing from 4 psi to the surface. At pressures less than 4 psi, there is very little effective bubble suppression. Almost 60% of the total decompression time is spent below this pressure. Almost 30% of the total decompression time is spent at less than 2 psi, and thus appears chiefly to be wasted time.

Another and more disturbing observation is that the OSHA tables provide a decompression schedule for "over eight hours" for each pressure level in the tables. Apparently, a tunnel foreman who had to stay beyond the length of his normal shift because of a construction problem or who conceivably might work a double shift or 16 hours, would still be eligible to decompress on the "over 8 hour" schedule. Sixteen hours under pressure in fact becomes a saturation exposure, and yet all of the "over 8 hour" schedules fail to provide anywhere near the proper amount of time for a decompression from saturation. As an example, the "over eight hour" decompression requirement for a working pressure of 20 psig calls for a total decompression time of 113 minutes. Twenty psig is equivalent to a pressure of about 45 feet of seawater. Current practice for saturation decompression from 45 feet would call for between 14 and 16 hours of decompression time with oxygen. Were the OSHA schedules to be used in a saturation situation, the results would be predictably disastrous.

At the Workshop, Mr. Arthur Chase produced a graph plotting decompression time in minutes against exposure pressure at sea level for 10 different exposure times. This graph was prepared by Straam Engineers, Inc. The graph showed the required decompression times to be quite irregular, but most notable was the fact that for a 6, 7, or 8 hour exposure at 26 psi, the decompression times were identical. The same held true for 2 or 3 hour exposures at 20 psi, 6 or 7 hour exposures at 18 psi, and the 7 or 8 hour exposures at 44 psi and 48 psi, whereas for the 7 or 3 hour exposures at 46 psi, the decompression times were different. No explanation could be

found for these inconsistencies. There were other examples of incongruity in the graph (which is appended). Mr. Chase, who is a professional tunnel engineer of many years' experience, pointed out that no engineer would have much confidence in the present OSHA schedules after simply inspecting the graph.

Additionally, the OSHA tables were calculated on the basis of only 3 half-time tissues, the 30, 60, and 120-min tissues. Other current schedules use six or more. Also, for the long exposures covered by these schedules, using the 120-min tissue as the longest half-time tissue is now considered inadequate. Mr. Edel stated that a 480 or 490-minute half time for the slowest tissue would be more appropriate, using that theoretical model.

Thus, the group concluded that the present OSHA schedules do need revision on the basis of the known high incidence of decompression sickness in all ranges, the appearance of dysbaric osteonecrosis at pressures over 36 psi, inadequate numbers and lengths of tissue half times, obvious discrepancies within the tables themselves, the gross inadequacy of using these tables to decompress from saturation and the long decompression exposures at pressures less than 4 psi, which do not conform to the current state of knowledge of decompression efficiency.

Alternative Decompression Schedules

There was a discussion concerning the possibility of using another set of decompression schedules already in use. It was acknowledged that the U. S. Navy Air Decompression Tables would not work because their time and depth ranges do not correspond to tunnel construction requirements. The USN exceptional exposure tables would come closer, but commercial experience with these tables has been very unfavorable. The exceptional exposure tables are still only to be used for emergencies. With regard to tables in use in other countries, the British developed the Blackpool Tables in response to problems with their earlier 1958 caisson tables. The Blackpool Tables were evaluated by the Canadians, who found that they had problems when times exceeded 5 hours. Even though the Blackpool Tables use deeper stops and are more efficient with regard to inert gas elimination than the OSHA tables, they still produce some dysbaric osteonecrosis at the longer exposures. Dr. Purdy explained that NIOSH was not interested in decompression schedules that produce even "a little bone necrosis." There are well-tested saturation schedules for air in existence, but these would be too lengthy for the non-saturation exposures in tunneling.

Dr. Behnke suggested the possibility of using a habitat and saturating tunnel crews at relatively modest pressures, and providing them with a 6 to 8 hour decompression from saturation at storage

pressure toward the end of their work week. Mr. Chase said that habitats could be constructed and would be practical on the larger jobs, but there might be a question of acceptance by the workmen, and further, saturation habitats might not be practical on smaller projects.

It therefore appeared to the Workshop members that there were no other alternative or totally satisfactory decompression schedules, domestic or foreign, which could be recommended without reservation to supplant the current OSHA schedules.

Probable Form of the Interim Tables

The first question to be answered in the development of an interim table was whether or not the new tables should use continuous decompression at varying rates or stage decompression. Continuous decompression has been traditional in the tunnel industry since the beginning of compressed air work. However, continuous decompression is much more difficult to control and therefore could not be accurately applied before the advent of cams or program tapes to ensure strict adherence to the proper rate of pressure reduction. Obviously, continuous decompression requires additional machinery (decompression controllers) and, in the event of equipment breakdown, would make conforming to the published table difficult. On the other hand, stage decompression appears to coincide less with actual physiologic processes, in that inert gas is not known to leave the body in stages. Mr. Chase favored using continuous decompression, whereas Mr. Edel pointed out that there are so many variables in the human body that stage decompression is not noticeably unphysiologic. Dr. Kindwall agreed with Mr. Edel, stating that stage decompression would not require cams and tapes and the whole decompression profile could be more easily monitored when the recording graphs were inspected. The Workshop committee decided that stage decompression was probably more practical.

Dr. Behnke suggested using oxygen-during decompression and the panel discussed whether or not an oxygen variant of the new interim tables should also be developed. It was pointed out that at some of the higher pressures and longer exposures, oxygen might be necessary to make the tables commercially acceptable because of the long decompressions required if air only was breathed. There was a great deal of discussion concerning the safety of oxygen decompression for tunnel workers, its acceptance by contractors, and the questions of oxygen toxicity. Mr. Chase pointed out that for insurance reasons, contractors would be unwilling to take the responsibility of using oxygen decompression, at least initially. However, after the first contract or two in which the government or some other body had insured this technique, they would be quick to "jump on the bandwagon." Overboard oxygen dump systems would be required if oxygen was used, and very strict regulations would be required to

ensure safety. The group decided that Mr. Edel should produce an oxygen variant of the new interim tables.

The use of special decompression changes or "long locks," in which men could take showers, change clothes, watch T.V., or play billiards during the last part of their decompression was also discussed. This equipment means that the men would be ready to leave as soon as the lock door opened. However, such large chambers, although excellent for some jobs, would not be feasible on smaller jobs.

The committee also specified that the new tables should be designated for sea level use only, and that they would not be adequate at high altitudes.

Use of Proprietary Methods for Determining OSHA-Approved Schedules

The feasibility of NIOSH or OSHA approving decompression schedules developed using proprietary methods was also discussed. Could OSHA approve such tables in the first place, not knowing how they were derived and what the legal ramifications would be? It was pointed out that a precedent has already been set in this area by proprietary commercial diving decompression schedules, which are used without objection by OSHA. Furthermore, tables are derived in commercial diving using proprietary formulas and are put into commercial service without testing. Again, this practice has met with OSHA approval. Mr. Edel has developed tables, using proprietary methods, that have been used by NASA, the U.S. Navy, and foreign navies. Dr. Purdy reminded the group that it is not a computer which must be relied on in a field that is constantly changing, but rather the reputation and record of the individual preparing the decompression schedules. Thus, NIOSH could quite properly give approval to a set of decompression schedules, even though proprietary, if they had been prepared and examined by individuals well known and experienced in the field. He noted that at the present time there are no better criteria to follow. The question of how the Workshop group could be sure that any interim decompression schedules were the best possible was also raised. It was pointed out that the group had not been tasked to produce "the best possible table," but had simply been asked to produce something better than what existed. This corresponds to a good - better - best situation, in which initially the present OSHA tables were "good" because they did not produce aseptic necrosis between 1963 and 1973. Now that they have not been able to sustain that record, it is necessary to look for something better than the original good tables. The best table cannot be known in advance and may not be developed for many, many years.

Conclusions of the Workshop Committee

Members of the committee felt that interim tables that are objectively better than the present tables could be produced to decompress compressed air tunnel and caisson workers. In view of the present findings with the currently enforced OSHA schedules, it is most desirable that interim tables be developed. The group further agreed that even though the new interim tables use proprietary methods, this is acceptable as long as the individuals preparing the tables are qualified. The committee felt strongly, however, that any interim tables adopted or approved by NIOSH should only be considered interim schedules, and their promulgation should depend on thorough testing in the laboratory. Without a long-term study to evaluate their use, the interim tables should not be officially promulgated.

After much discussion it was agreed that Mr. Edel, upon receiving a contract from NIOSH, should generate the interim tables within a 2 to 3-month period, and that the Workshop committee members would meet again to evaluate the results of his efforts. The new tables would be checked to see if the known inadequacies, inconsistencies, and defects of the present tables had been removed and to evaluate the decompression profiles in light of current decompression practice. Then, if the group of experts felt that the tables represented a definite and documented improvement over current schedules and conformed reasonably to present day concepts of adequate decompression, the schedules could be made available to the public through NIOSH.

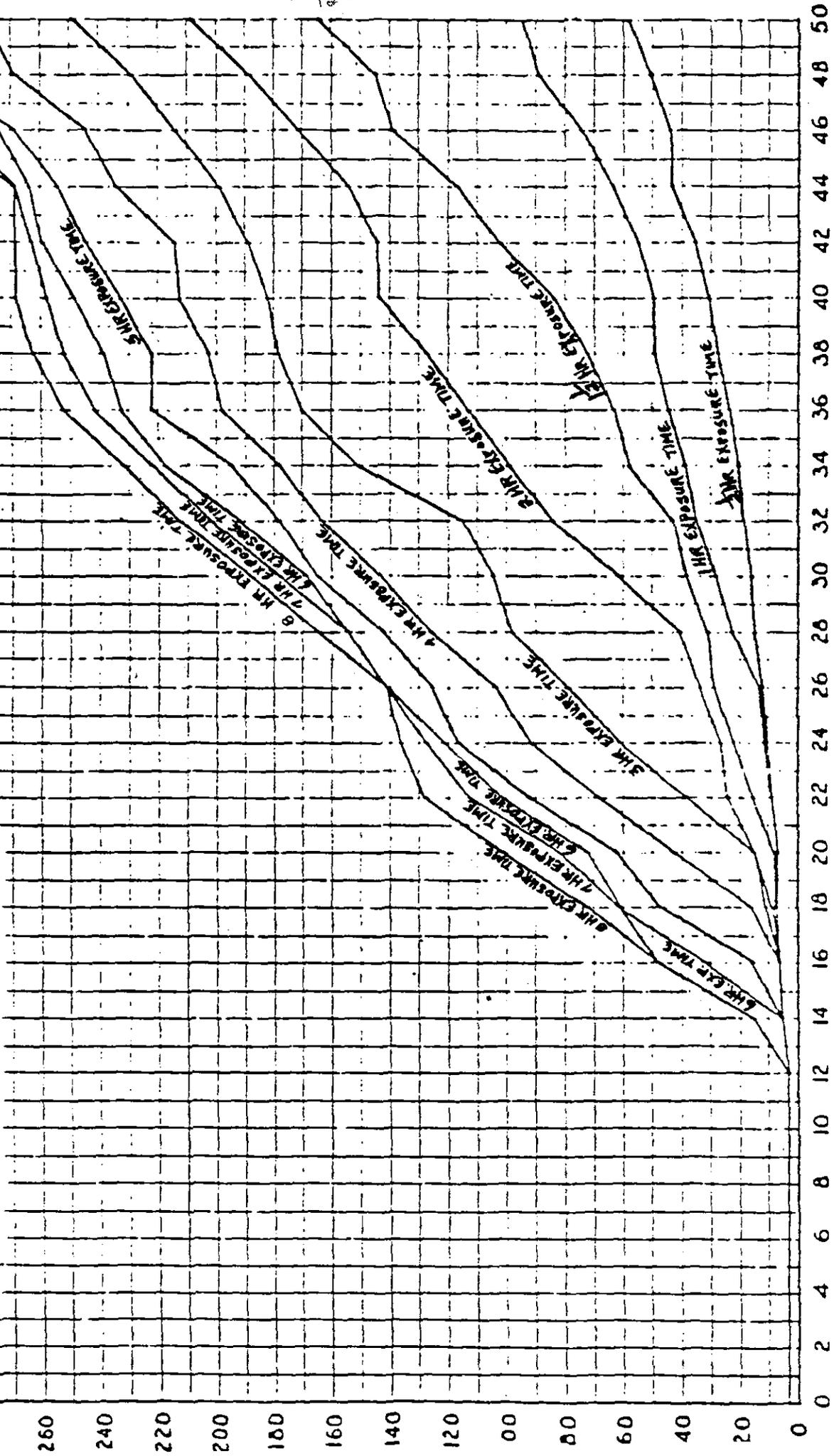
Instructions to Mr. Edel

A considerable portion of the Workshop was devoted to the details and requirements of decompression schedules from the contractor's point of view and also to the conditions actually known to occur in the compressed air tunnel environment. On the basis of these discussions, Mr. Edel was to produce a set of decompression schedules, observing the following parameters:

1. Schedules are to be calculated for 2-psig increments from 14 to 50 psig.
2. Schedules are to be calculated for half-hourly increments of exposure from one-half hour to eight hours, with provision for saturation at any given pressure level.
3. An oxygen variant of the air decompression tables is to be produced.

4. The tables are to be designated for sea level use only (which means they could be used at maximum altitudes of only 800 to 1000 feet above sea level).
5. The temperature in the tunnel is assumed to be above 60° Fahrenheit.
6. Calculations are to assume that the worker has been exposed to four previous days of ordinary shift work at the same pressure level, thus taking any residual nitrogen into account.
7. The tables should be designed only to take one exposure per worker in any 24-hour period into account.

Decompression times taken from:
 Decompression Table No 1, page 8661
 Federal Register, Vol. 44, No. 29
 Department of Labor - OSHA



EXPOSURE PRESSURE, PSIG AT SEA LEVEL

APPENDIX XII

REPORT

TO

NATIONAL INSTITUTE FOR OCCUPATIONAL SAFETY AND HEALTH

ON

ASSESSMENT OF PROPOSED INTERIM DECOMPRESSION TABLES

FOR

CAISSON AND TUNNEL WORKERS

FROM

UNDERSEA MEDICAL SOCIETY, INC.

9650 ROCKVILLE PIKE

BETHESDA, MARYLAND 20014

8 AUGUST 1980

ASSESSMENT OF PROPOSED INTERIM DECOMPRESSION TABLES
FOR
CAISSON AND TUNNEL WORKERS

Report to
National Institute for Occupational Safety and Health

Purchase order 80-2452

Report edited by R.W. Hamilton and C.D. Gull

Prepared by
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9650 Rockville Pike
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1980 August 8

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I. INTRODUCTION

This study, along with an earlier one, explores the feasibility of producing and introducing an interim set of decompression tables for caisson and tunnel workers in the U.S. "Interim" tables are being considered as a means of reducing decompression sickness (DCS) and bone necrosis during the period of several years which will be needed to develop, test and implement new tables or an appropriately refined version of the current ones.

The situation is this. The current caisson and tunnel tables have not been found to be ineffective in preventing dysbaric osteonecrosis in the range of working pressures up to around 36 psi, but recently cases of bone necrosis have come to light which have resulted from work at pressures greater than 36 psi (Kindwall, et al, 1979). In both the BART job and one in Washington state an unacceptable incidence of DCS in the working ranges deeper than 30 psi has been seen, and unpublished studies have shown that workers are experiencing but not reporting decompression sickness at depths as shallow as about 15 psi. Up to 26% unreported bends were noted in one study which permitted the workers to remain anonymous (Kindwall, 1979). These bends seem to be rather well distributed over the entire range of pressures deeper than about 15 psig, and are not concentrated in the high pressures.

The decompression tables in current use are those developed originally by Duffner and which became known as the "Washington State" tables. The same tables were adopted by Wisconsin and several other states, and are the ones adopted by OSHA and published in the Federal Register (Vol. 36, No. 75, 17 Apr 1971). They were a big improvement over earlier ones, and it was only after several years of use that any problems began to show up. The effectiveness of tables can only be determined by their being used, and if problems are late in showing up it is likely to be because they have not been used enough.

In response to these reports of bone necrosis at the higher working pressures, and of the continuing occurrence of decompression sickness, Dr. Alan H. Purdy of NIOSH contracted with the Undersea Medical Society to conduct a workshop study of the feasibility of interim tables. The first such workshop, held 1979 Jul 23 (Shilling, 1979), is discussed in the next section, and the second, held 1980 Feb 28-29, is the subject of this report.

The working group determined, on the basis of an examination of the proposed interim tables in the light of its collective experience, that the tables were likely to be better than the current OSHA tables, and that their release for interim use was feasible.

II. SUMMARY OF THE FIRST WORKSHOP

The work order from NIOSH to UMS, No. 79-3851 and dated 1979 Aug 2, called for determination of "the feasibility for developing interim decompression schedules to replace the present federal schedules which have been shown to be dangerous to tunnel workers." According to the work order the interim schedules should have

- 1) A maximum decompression sickness rate of 5% with non-serious classification.
- 2) A maximum dysbaric osteonecrosis rate of 4% with shaft lesions only.
- 3) A tunnel or caisson depth of at least 112 feet (50 psig).

The group convened included physicians experienced in medical management of tunnel jobs, an engineer with extensive tunnel experience, researchers in development of decompression procedures and representatives from federal agencies.

The group dealt with two main topics. The first was to evaluate whether interim tables could be produced and implemented and whether they could be expected to meet the criteria, and the second was to prepare definitive specifications for the computation of such a set of interim tables.

These tables were to be computed by Mr. Peter Edel, who was to do this as a subcontractor under a NIOSH contract to St. Luke's Hospital, Milwaukee. Principal Investigator on the contract is Dr. Eric Kindwall; its objective is to use laboratory testing with ultrasound and nitrogen washout studies to validate a set of tunnel and caisson tables which can eventually replace the current OSHA ones. The "interim" tables being evaluated by the workshops can be a starting point for this development program. It is proposed that these be introduced as optional, interim, tables by means of OSHA's Current Information Bulletin.

In addition to reviewing the statistics given in the introduction, the group discussed other deficiencies in the current OSHA tables, including the hypothetical half times used in their computation, the lack of a true "saturation" profile for long shifts, and inconsistencies between tables. One aspect of the current tables with which Dr. Kindwall strongly objects is the long time spent at relatively low pressures (under 4 psi).

No existing set of tables known to the group and in current use were considered to be acceptable as a substitute for the OSHA tables. Of particular interest are the Blackpool tables used in the U.K. These do in fact compare favorably with the OSHA tables, especially for shifts of less than 4 hours, but are nevertheless felt to allow too high an incidence of bone necrosis.

The use of saturation procedures was considered a promising prospect for some of the larger jobs, but this would not meet the need for routine tables.

The central question asked of the workshop was whether it would be possible to calculate a set of interim tables which are definitely no less safe and which can reasonably be expected to result in less DCS and bone necrosis than the current ones. It was agreed that this was feasible. No one felt that this was likely to result in the best possible tables, but chances were considered quite good that a set better than the OSHA tables could be devised. It was agreed that it would be safe and proper to offer tables produced in this manner for optional interim use, but that long term evaluation would be necessary before they should be promulgated as "official."

The matter of evaluation or "testing" of a set of decompression tables was discussed with regard to the proposed program. The group agreed some testing was necessary, but it was pointed out that a great many tests are needed to establish an incidence with any degree of confidence. Decompression tables based primarily on experience -- hence empirical -- could be considered as "pre-tested". Laboratory tests which use DCS in human subjects as the experimental "end point" serve the important purposes of disclosing blunders and satisfying ethical formalities, but they are of little value in defining low level incidences. Ultrasonic bubble detection or other measures of assessing decompression adequacy may greatly amplify the information obtained from tests, and their use on the longer range project was endorsed. The group agreed that the only way at the present time to evaluate decompression tables fully is through their use in the field.

It has to be considered also that laboratory tests of this type of pressure profile expose the experimental subjects to a significant but acceptable chance of getting bone necrosis. Although tests might cause bone necrosis it is unlikely that they might do so soon enough to be of experimental value, and to do this intentionally would of course be unethical. The group feels that tables which eliminate DCS will go a long way toward complete elimination of bone necrosis.

The computational methods used by Mr. Edel are based on the widely used Haldanian or neo-Haldanian principle, but the specific computations and many of the parameters used are proprietary. The group was clearly not happy that they could not review these details, but they acknowledged that this was "industry practice" for decompression computations. Because they know Mr. Edel and his experience they reluctantly accepted the situation. The group recognizes him as one of a very few who are qualified to compute these tables.

The group came up with certain guidelines for Mr. Edel to use in constructing the tables. Staged rather than continuous ascent was selected, but some prefer continuous; the choice is primarily operational, as it seems to make little difference physiologically. Stops are to be for 2 psi increments from 14 to 50 psig, and times every half hour to 8 hours. Saturation decompression shall be possible from any pressure. An oxygen variant of the tables is to be provided. The tables need only be useable at sea level. Tunnel temperature is assumed to be 60° F. From a gas loading point of view the tables are to assume each worker has been exposed to the same profile the preceding 4 days; only one shift per 24 hour day is to be performed by each worker.

The workshop adjourned with the understanding that they would have an opportunity to review the tables produced by Mr. Edel, and that if in the judgement of the working group they meet the requirements for interim tables as discussed the group would endorse them for use.

III. REPORT OF THE SECOND WORKSHOP

This meeting was convened to review and discuss the decompression tables produced by Peter Edel following the first meeting. It was requested by Purchase Order 80-2452, which had the same specifications as the first (above) except that a fourth was added:

"If necessary, make recommendations for modifications of the interim tables to meet specifications 1) through 3)."

A. Autodec G-3 tables

Using the Autodec computer program proprietary to Sea-Space Research Company, Inc., and modifying it as necessary to meet the specifications determined at the first meeting, Mr. Edel produced three sets of decompression tables. These are designated G-3A for the air tables, G-3B for those using oxygen, and G-3C for the saturation decompression profile. They are found in the appendix to this report, along with some descriptive information about assumptions used in computing them and instructions for their use.

Shortly before the meeting these tables were sent to participants in the second workshop.

B. Participants

Dr. Albert R. Behnke, Peter Edel, R.W. Hamilton, Ph.D., Dr. Eric P. Kindwall, Joseph LaRocca, Alan H. Purdy, Ph.D., and Dr. C.W. Shilling were present at the first meeting and were also at the second. Also at the second meeting were:

Lorin K. Lorig,
STRAAM Engineers, Inc.
Lexington Building
11900 Parklawn Drive
Rockville, MD 20852

Allan "Ike" Martin
OSHA, U.S. Department of Labor
Washington, DC 20210

Richard Vann, Ph.D.
F.G. Hall Laboratory
Duke University Medical Center
Durham, NC 27710

Mr. Arthur Chase was unable to attend the second meeting, but his technical specialty was covered by Mr. Lorig.

The discussion showed that this group were dedicated, experienced professionals who sincerely wish to reduce the incidence of decompression sickness and dysbaric osteonecrosis in caisson and tunnel workers to as close to zero as possible without making tunnel construction physically and economically unfeasible.

It is relevant to point out that the working group includes four people who engage in decompression work as their primary professional activity, and others who are concerned with it frequently. Decompression is still far enough from being an exact science that there are many approaches to its different facets and a variety of valid opinions about how to do it. It is unrealistic from the start to expect a group of this sort to agree on more than a fraction of the questions it may consider on this subject. The group, however, did agree that it is difficult to judge the merit of a new decompression procedure, and impossible to do it in a really quantitative way without actual field use.

It is reasonable to expect the groups opinion to say whether the G-3A tables appear to be better than the OSHA tables or not (or at least no worse), and what specific steps might be taken to improve the chances that they would be better. This was done.

Another aspect of this commentary is the social difficulty created by the situation in which several professional workers, all of whom are long time friends, openly must critique the work of a colleague (and competitor). This is awkward at best, but is made even more difficult by the fact that the critics in the group are not well enough informed as to what the G-3 tables are and how they were derived for them to be as specific as they might like to.

C. Need for improvement

This and subsequent sections report the deliberations of the working group in the 2-day workshop. A draft report of the meeting circulated on 1980 May 30 elicited comments from some members of the group, but most of these comments dealt with matters which have been corrected so are not included specifically. Comments submitted by mail after the meeting were not subject to rebuttal by other members of the group so they are identified separately in the report. Some material in the second meeting which is redundant with the first is not reported a second time.

The meeting began with a reminder by Dr. Shilling about its objectives, that the group was to determine if the new interim tables were good enough to be used until new ones can be developed.

Next Dr. Kindwall reviewed some specific cases of bone necrosis from his report (Kindwall, 1979), which add further support to the premise on which the project is based. He reported that he was able to obtain a set of bone x-rays on 21 of 30 workers who had worked at greater than 36 psig on a contract in Milwaukee which worked to 43 psig. The incidence of bone necrosis in this group was 33%. One portentous aspect of his findings was that several of the cases had had clean x-rays several years ago, had stopped compressed air work, then two or three years later began to show lesions, some of them disabling. Another interesting and puzzling aspect of his findings is the observation that there are few cases of DCS -- bends -- at pressures above 36 psig, but that all the potentially disabling bone necrosis found is in workers exposed at this pressure or higher. Consistent with earlier experience, no correlation was found between specific locations of bends and necrosis, and bends (DCS) do not seem to be a precursor of bone involvement.

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The group reaffirmed their earlier conclusion that improvements are needed in the tables required by OSHA. They further acknowledged that interim tables will have to be based on experience and judgement, and that there is at present no way to predict the degree of improvement or predicted incidence of either DCS or osteonecrosis. It was reiterated that OSHA would find it difficult to issue new tables or condemn the current ones without NIOSH's recommendation. However, NIOSH can act by publishing interim procedures in its Intelligence Bulletin as a matter of public information with probable benefit.

New tables could be used with a variance, and OSHA can invite applications for variances along with an announcement of the new, optional tables. Dr. Purdy pointed out that if he is aware of procedures which will improve the safety and health of workers he is required by his job to disseminate them.

D. Comments on the G-3 tables

Dr. Behnke spoke out for "deeper stops," or breathing air at higher pressures for a longer time during the decompression. Mr. Edel said when he tried computing with deeper stops it provided "no greater safety." He would not elaborate on how he reached this conclusion. Dr. Vann disagreed with the need for deeper stops, but Dr. Hamilton felt that they might be an improvement and was not satisfied with Mr. Edel's answer. For example, after 2 hours at 50 psig the OSHA table begins to slow the initial rate of ascent at 34 psig, while the G-3A calls for the initial ascent to go all the way to 20 psig; he feels this "first pull" might well be enough to trigger bubble formation. Dr. Behnke made some specific recommendations about how the tables should be computed (or should have been computed). One suggestion was that a 15 minute compartment be added to the 30, 60 and 120 minutes used by Duffner, in order to slow the initial ascent. (It is likely that Autodec uses a shorter first compartment half time than 15 minutes, but this was not brought out at the time.)

Dr. Kindwall had expressed earlier his feeling that the current tables, especially the shorter shifts, spend too much time at low pressures -- say between 4 psig and the surface. This might be corrected by spending more time at the deeper stops. Thus there are two aspects to the "deeper stops" requirement, first a need to reduce the speed and magnitude of the first ascent step, and next to reduce the amount of time spent at the shallow stops. The group felt in general that the G-3A tables spend a good portion of the decompression time at the shallower stops ("like treatment tables").

Dr. Hamilton suggested by mail that the sleep stops be included only in shifts requiring a total time of work plus decompression of 16 hours, rather than the 8 presently used.

There was a general feeling among the group that any of the OSHA tables which "work" should be retained. There is little reason to believe that any of the current tables are overly conservative, and if practice has shown that certain ones are safe then there is no reason to discard them. This might be interpreted on the basis of total decompression time, which is generally but not completely correlated with successful decompression. That is leave all the OSHA tables that are longer than the new G-3A's. It

was felt that the interim tables should not be appreciably shorter than the existing OSHA tables in the shallow range (less than 30 psig), but that for pressures higher than this definite increases in decompression time were called for. Dr. Vann produced a chart (sent in by mail) which shows that in the shorter, shallower part of the pressure range, roughly less than 3 hours and shallower than 26 psig, the Autodec tables are shorter than the OSHA tables.

Although the group in the first meeting agreed that these tables should operate with stops rather than a series of continuous decompressions, there was some support for the latter method. The possibility of offering both methods was suggested.

There was general agreement that there would likely be subsequent changes in the tables originally issued as "interim."

E. Oxygen, saturation, and the split shift

Dr. Behnke advocated use of oxygen to speed decompression and to provide more working time in an 9-hour shift. The group agreed that oxygen breathing would allow for a faster decompression and hence a longer work period within an eight hour day. They unanimously endorsed its use as a means of improving decompression safety. Mr. Lorig feels that oxygen might be feasible and well accepted because of the big time saving (about 50%). The long air decompressions in one way are a negative safety factor, because the shorter shifts cause more people to be exposed and some of these have inadequate work experience and may not be as safe on the job. It was pointed out that oxygen use might not allow longer work periods in all states; for example, in New York the shift time is limited by union contract and would not be changed (easily) by the advent of new tables.

Dr. Behnke feels oxygen might also help "keep nitrogen out of the bones" when used with a split shift. The split shift allows the workers to return to surface pressure for a lunch break, then finish the work day with a second shift. This is in effect a partial decompression, and should significantly reduce the total gas load which has to be removed at the end of the day if the second shift is not very long. There is nothing fundamentally wrong with the split shift concept, but there is limited documented experience in its use; it has to be managed so as not to create bubbles which will be difficult to get rid of later. The split shift method is not under consideration for this immediate project, but it remains an attractive option.

The group agreed that the G-3B tables meet the need for oxygen tables, although it was acknowledged that no one really knows precisely how much "credit" to give for the use of oxygen in a decompression. The G-3B tables appeared to the group to be safe, but the reservations about the depth of the first stop still apply. A maximum CPTD of about 900 was recommended for daily work (this is a measure of oxygen exposure and should be taken into account in the table computation). It was suggested that oxygen breathing is more effective at pressures above 15 psig (but below toxicity limits), and frequent air breaks were recommended by some participants. Also, appropriate fire safety rules need to be developed and implemented if oxygen breathing is to be used.

Dr. Behnke presented his views on the use of the habitat or NOAA OPS concept, an approach which he has been promoting for many years (30 years before the NOAA OPS operation!) By this method the workers would live in a chamber at some intermediate pressure between surface and the work site and would make pressure excursions to go to work. For the range of pressures used or contemplated in tunnel work they could perform long shifts; this could be carried out for a few days and this crew could be decompressed and replaced by another. The group agreed that the G-3C saturation decompression procedure provided would make this concept practicable and that it was therefore a valid option for the proposed interim procedures.

The group seemed quite pleased with the appearance of the G-3C saturation profile, but not much time was spent discussing it. If anything, it was felt to be a bit too conservative.

F. Testing

Dr. Behnke felt the G-3 tables should be tested before being used. In response to this Dr. Vann pointed out that hundreds of identical tests would be required to establish with confidence that a given profile met the requirements for less than 1% DCS. Dr. Hamilton made the point that the value of "testing" of decompression tables was misunderstood by most people. A few laboratory decompressions will disclose if there has been a catastrophic blunder in the computations, but the number of tests required to establish an "incidence" with proper statistical confidence is prohibitive.

Dr. Kindwall offered to perform a few tests under the same conditions as a specific job, if a contractor wants to use the new interim tables on a job. This is an important point, and in effect can answer the need for testing of the interim tables. If this is done then any use of the interim tables would be preceded by some highly appropriate tests. There are few enough such jobs that Dr. Kindwall can easily accommodate them within the scope of his contract. A few tests of a specific profile are more valuable than a large number scattered about a complete set of tables. This offer should be stated along with the issue of interim tables.

Dr. Behnke reiterated his feeling that the G-3 tables should not be released without testing. He did not answer the point about the value of a few tests in establishing incidence. The testing recommended at the meeting called for 10 subjects to be exposed for 10 consecutive days at 36 psig for 3 hours.

Dr. Behnke developed his views more fully in an extensive set of memos sent by mail. After the draft report he reiterated his opposition to the issue of interim tables of any sort without testing. This is a matter of principle, because he feels with the group that the Autodec tables are likely to be an improvement over OSHA, especially if they are redone to include the suggested changes. He feels that 100 tests (as proposed at the meeting) would normally be expected to show perhaps 7 or 8 cases of DCS. (He did not cite this expected incidence at the meeting.) He advocates 100 clean exposures before issue. He offers two options to the G-3A tables. First is a means of making the appropriate corrections to the Blackpool

tables, the other is a modification of the OSHA tables in the directions discussed at the meeting. His proposed changes look quite reasonable, but he did not cite a quantitative rationale for them. [Editor's note: Although it was not clearly stated at the meeting, it seems that many of the group agree with the principle that small modifications of tables that are close to being satisfactory may be a better means of improving decompression than starting over. From the discussion and opinions offered, it is likely that had Autodec produced tables looking like Behnke's modifications the acceptance would have been far more enthusiastic.]

Although Mr. Edel did not go into detail about the Autodec program, he discussed its concept: It uses data from many previous dives and pressure exposures to draw the profiles. It is entirely empirical in its operation, although a mathematical model is used to interpret the data and compute the resulting tables. In addition to the fact that the profiles are based on experience to begin with, Autodec's results have been compared to tables from other sources. Thus the use in the field of an Autodec table by no means constitutes decompression with an "untested" table. Such might be the case if a new model or theory were used, but for a system based entirely on past experience and with a proven low level of incidence in other applications, controlled field use of these tables is entirely appropriate. They are, in a sense, pre-tested. It was brought out that there is plenty of precedent for issuing tables without laboratory tests, that all of the tunnel tables in current use were implemented without them.

These comments about testing apply to cases in which the end point is decompression sickness. Other techniques are available, and Dr. Kindwall plans to use some of these in the testing and evaluation program which is proposed to result in a more refined and tested set of tables; these might well be adopted by OSHA as mandatory. (Dr. Hamilton warned against the use of terms like final or permanent, since a decompression table may never be perfect, and even if it were it would take years of use to establish that fact.) The testing Dr. Kindwall plans to use was reviewed at the first workshop; it consists of using nitrogen washout and ultrasonic imaging of bubbles to establish objective criteria as to the effectiveness of the decompressions, and to use these factors as well as any incidences of DCS to determine the relative effectiveness of the various tables. It was suggested that altitude provocation be considered as a technique; this allows the results of different tables to be compared with higher sensitivity and less risk.

RECOMMENDATIONS

The Undersea Medical Society Tunnel Decompression Working Group makes the following recommendations as a result of its deliberations in two workshops:

1. We concur that the current OSHA tables for tunnel and caisson work need improvement. As far as we know there are no decompression tables in current use which are acceptable for this type of work and which have a suitably low incidence of decompression sickness and dysbaric osteonecrosis.

2. We acknowledge that field use of provisional tables derived from previous experience is an effective means of bringing new decompression technology into use, provided the tables introduced in this manner are sufficiently like ones with a proven record, and that results of early use are monitored and results fed back. We see an effective mechanism for this in the variance process required by OSHA for use of interim tables, coupled with the ongoing development program of Dr. Kindwall's contract, and we encourage that a feedback arrangement be implemented. We presume that this plan is consistent with continued, ongoing improvements.

3. We assessed the G-3A air decompression tables produced by Mr. Peter Edel in relation to the current OSHA tables. As a result of our examination of the tables, and on the basis of the methods used to derive them and the experience behind them, we feel subjectively that the G-3A tables in general use can be expected to result in less decompression sickness and bone necrosis than the current OSHA tables.

4. The group, with the possible exception of Dr. Behnke, acknowledges the feasibility of issuing of the G-3A tables on an interim basis, along with a laboratory program for spot checks of the specific profiles applicable to jobs to be performed with the interim tables. We recommend the G-3 tables as a starting point for a long term program to replace the current OSHA tables.

5. We feel that certain improvements might make the G-3A tables even more effective:

a. Parameters should be adjusted so as to reduce the magnitude of the initial ascent. Thus ascent should not exceed, substantially, the initial ascent used in the OSHA tables on which experience has been successful.

b. Where possible, without exceeding criteria for safe decompression, more time should be provided in the middle part of the decompression and less in the shallowest (4 psig) stop.

c. The program should be adjusted so that tables with decompression times substantially shorter (e.g., by more than 10%) than the OSHA tables are brought in line with the established times until the safety of the shorter times has been demonstrated.

6. We endorse the release of the G-3B tables using oxygen as interim tables. Modifications recommended for the G-3A tables can be applied to the G-3B tables as well. Some suggestions are offered regarding oxygen breathing. Fire safety procedures should be included with any release of oxygen tables.

7. We endorse the release of the G-3C saturation decompression table and encourage its use.

8. We recommend that NIOSH request the continuation of this working group to monitor the continuing development of improved tunnel and caisson decompression procedures.

Interim decompression tables

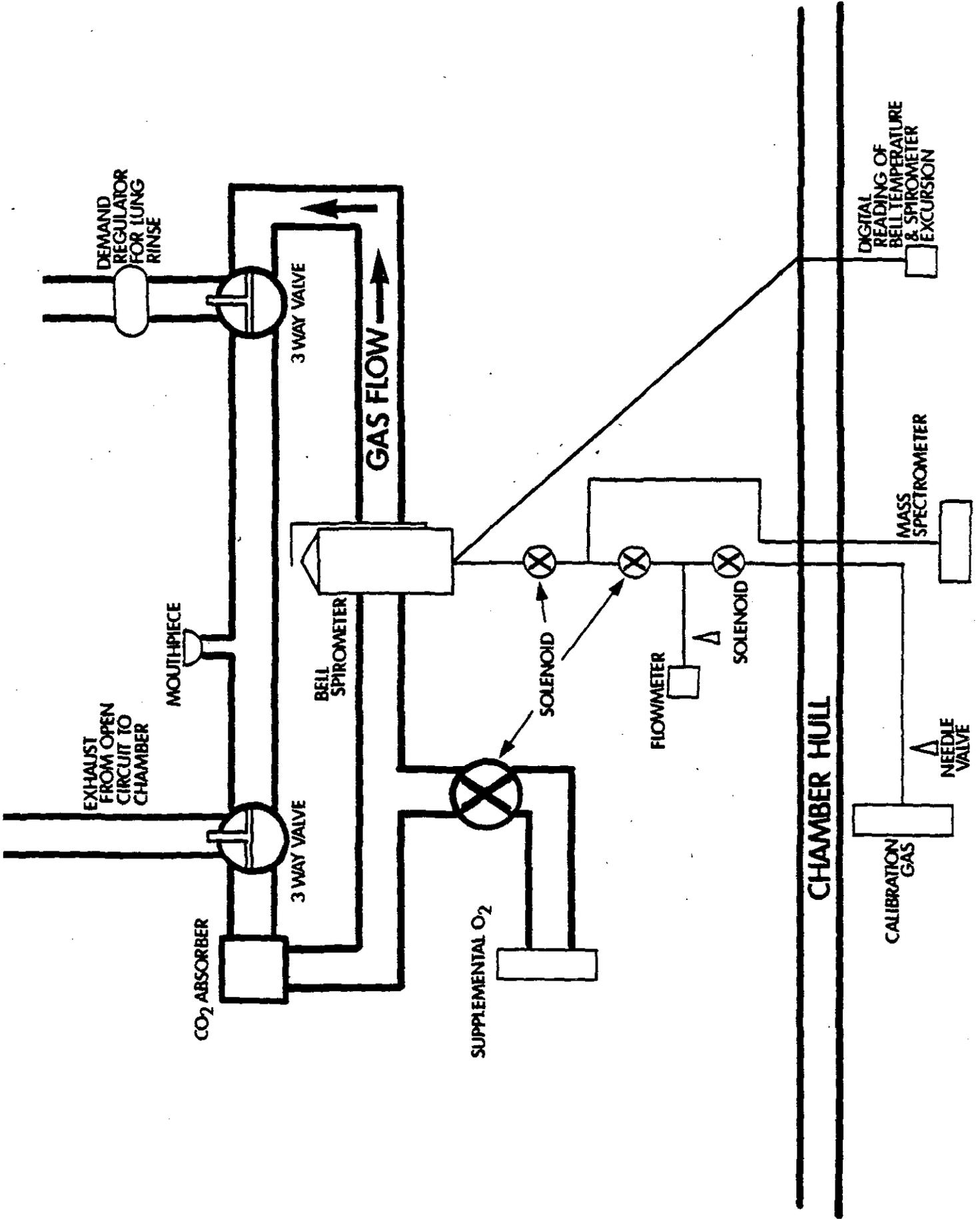
V. REFERENCES

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- Shilling, C.W., editor. A study to determine the feasibility for determining interim decompression tables for tunnel workers. UMS Publ. 28(TU)9-4-79. Bethesda, MD: Undersea Medical Society, 4 Sep 1979.
- Walder, D.N., and R.I. McCallum. An objective appraisal of the Blackpool (U.K.) and Washington State (U.S.A.) decompression tables. In: 5th International Hyperbaric Conference Proceedings 1973, edited by W.G. Trapp, E.W. Bannister, A.J. Davidson and P.A. Trapp. Vol. II. Burnaby, B.C.: Simon Fraser Univ., 1974.

APPENDIX XIII

GRAPHS AND DIAGRAMS

BREATHING CIRCUIT



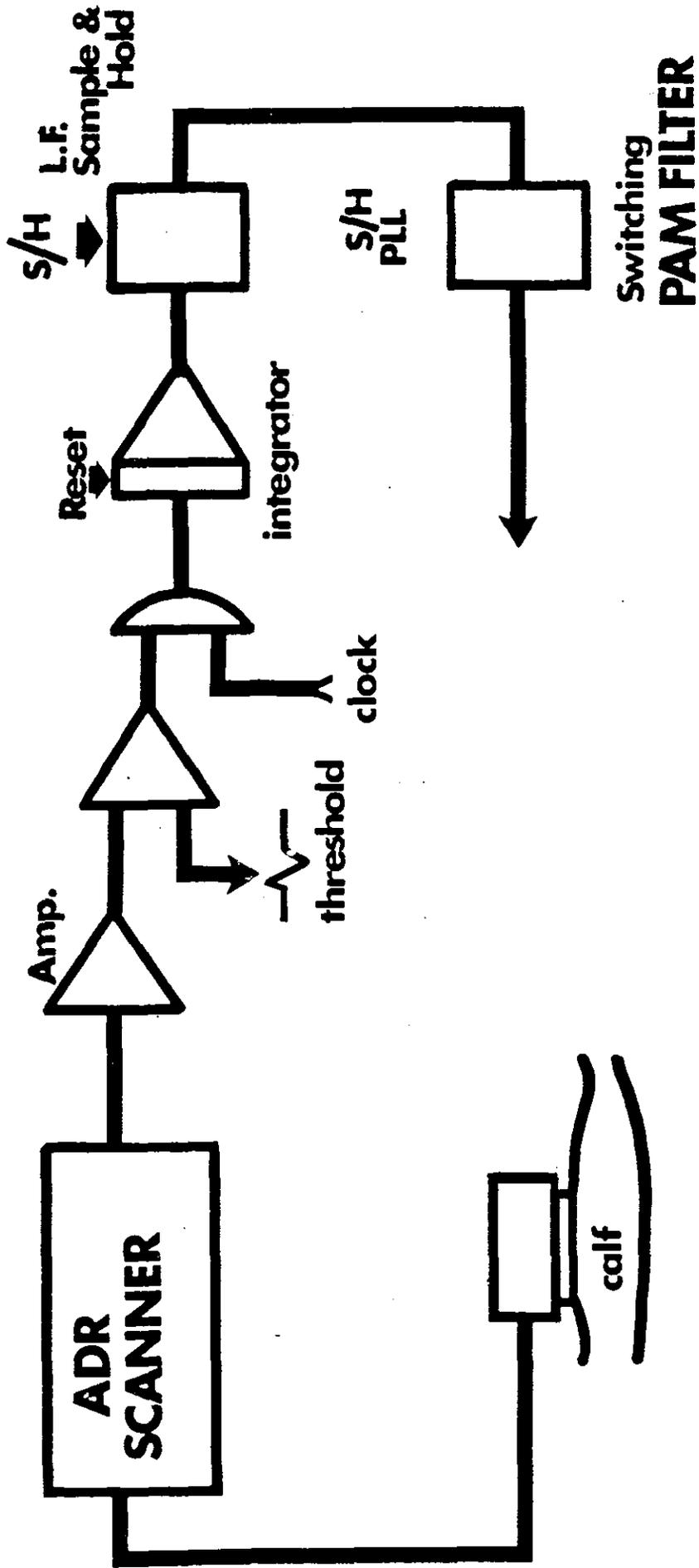
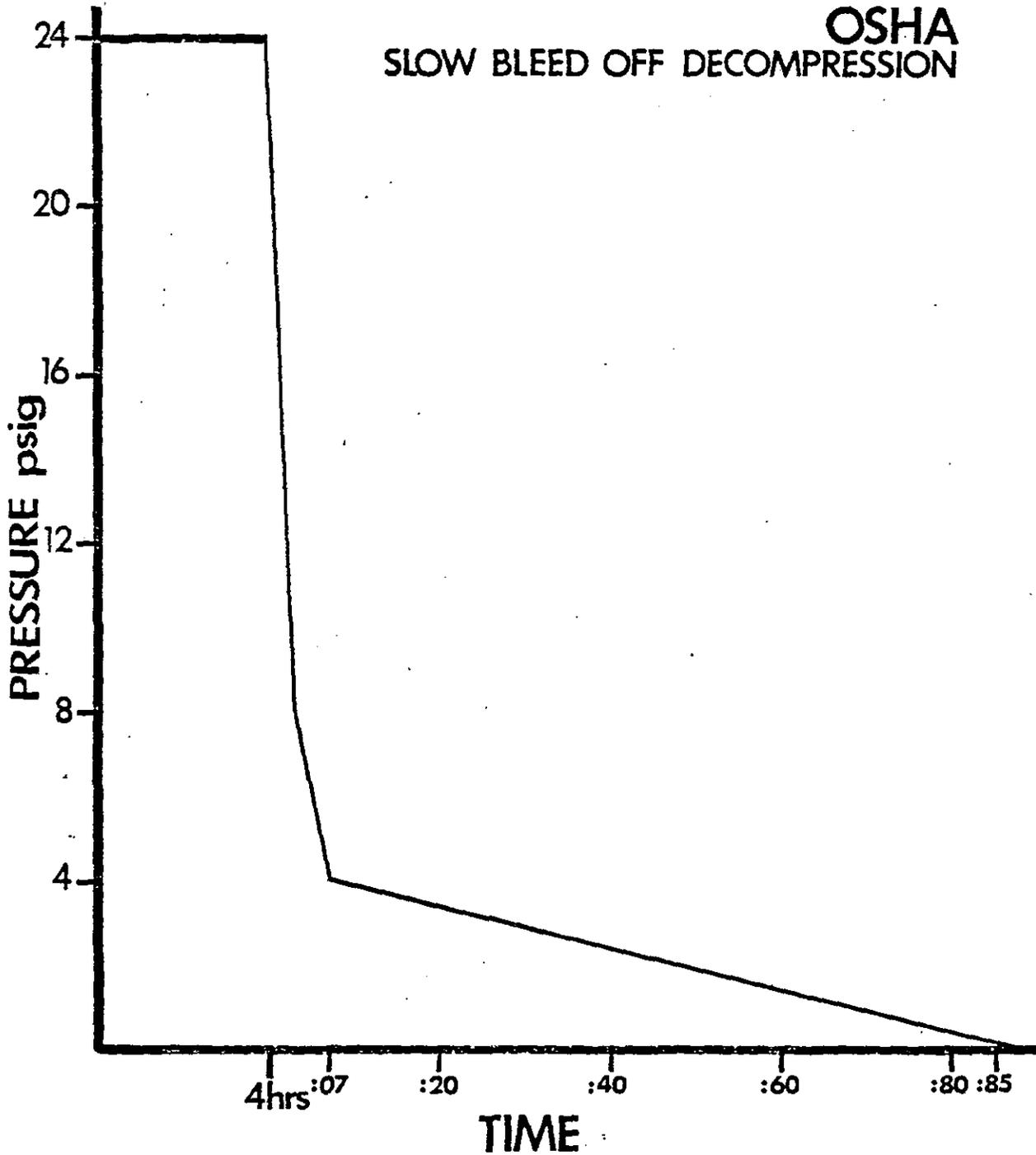


FIG. 2 - Schematic Diagram of Bubble Detection Circuitry.

GRAPH I OSHA

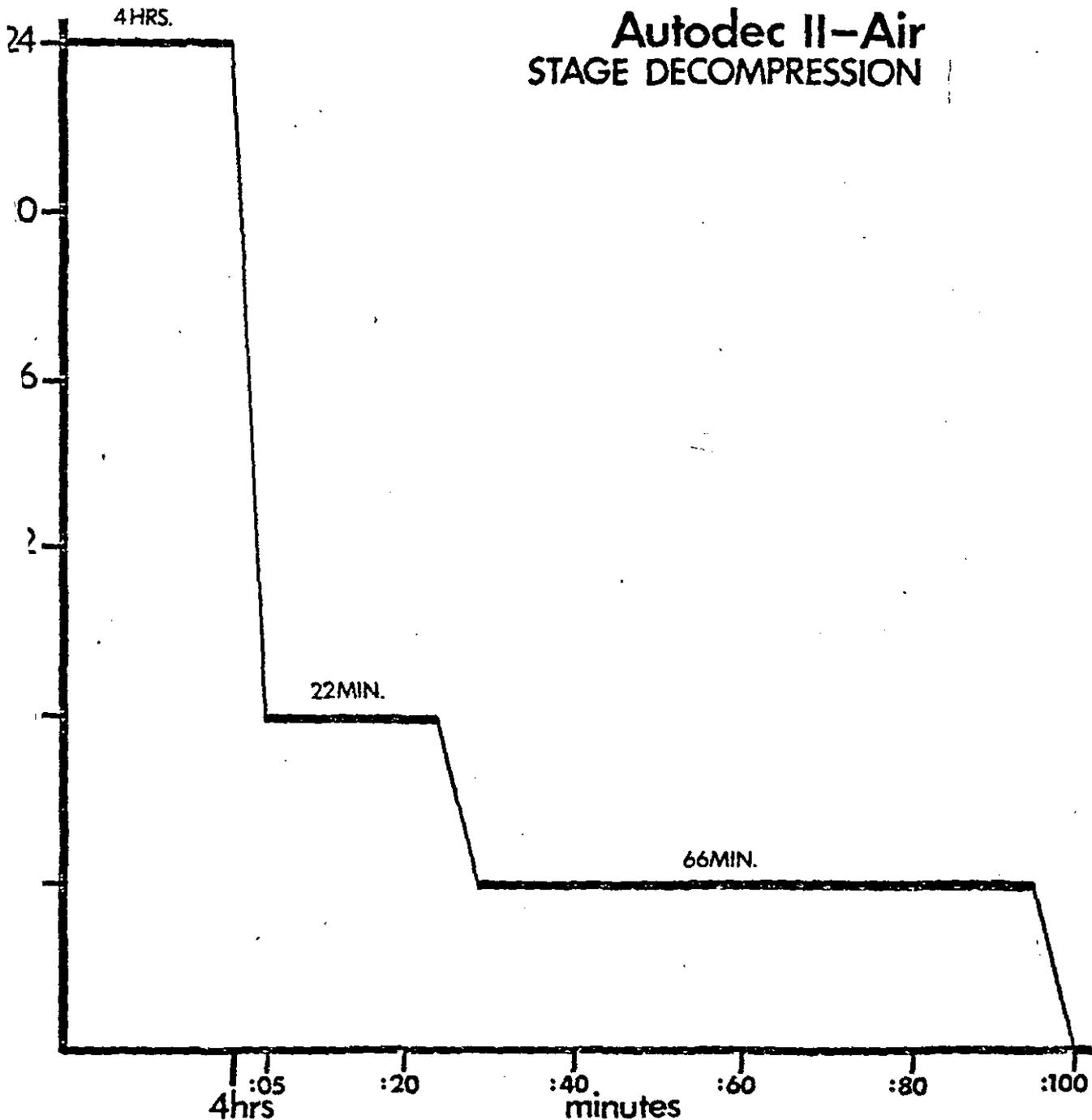
SLOW BLEED OFF DECOMPRESSION



GRAPH II

Autodec II-Air

STAGE DECOMPRESSION



TIME

GRAPH III
Autodec III - O₂

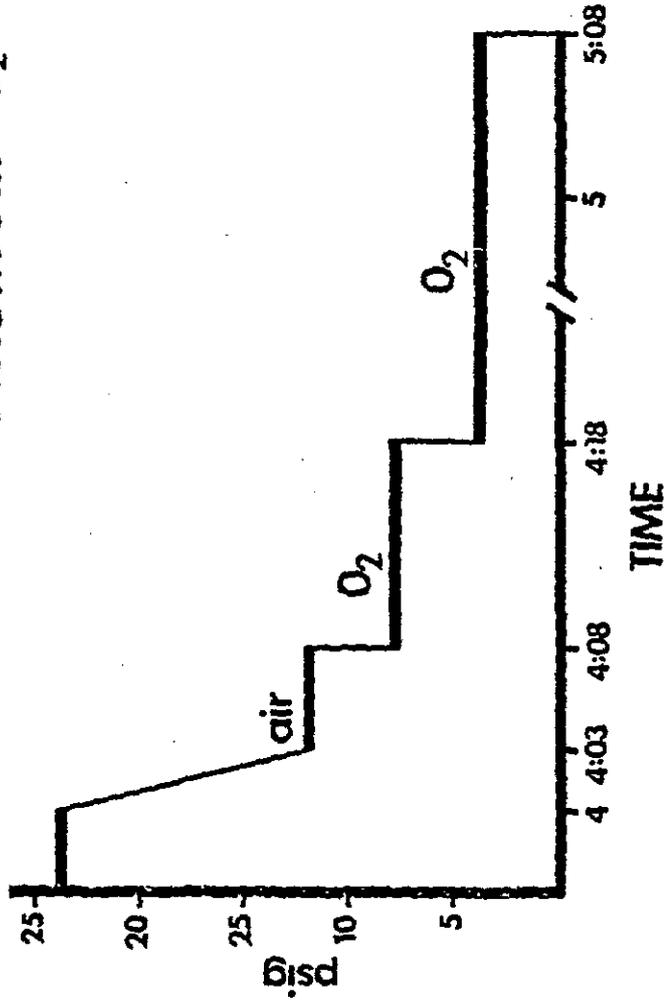


Fig. 5. - Autodec III-O₂ Decompression Profile for 24 pounds.

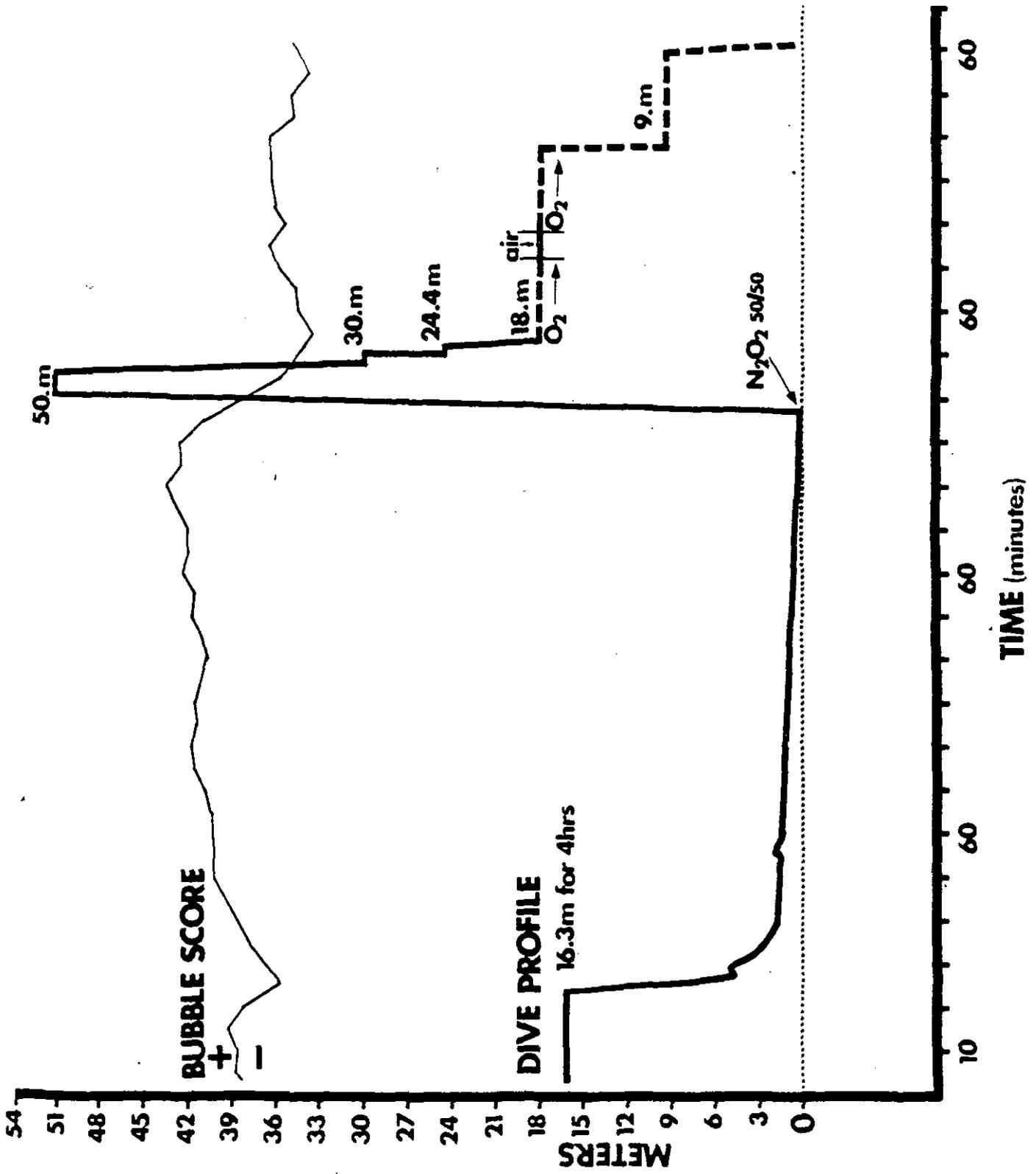


Fig. 6 - Bubble Formation with Decrease on Recompression (OSHA)

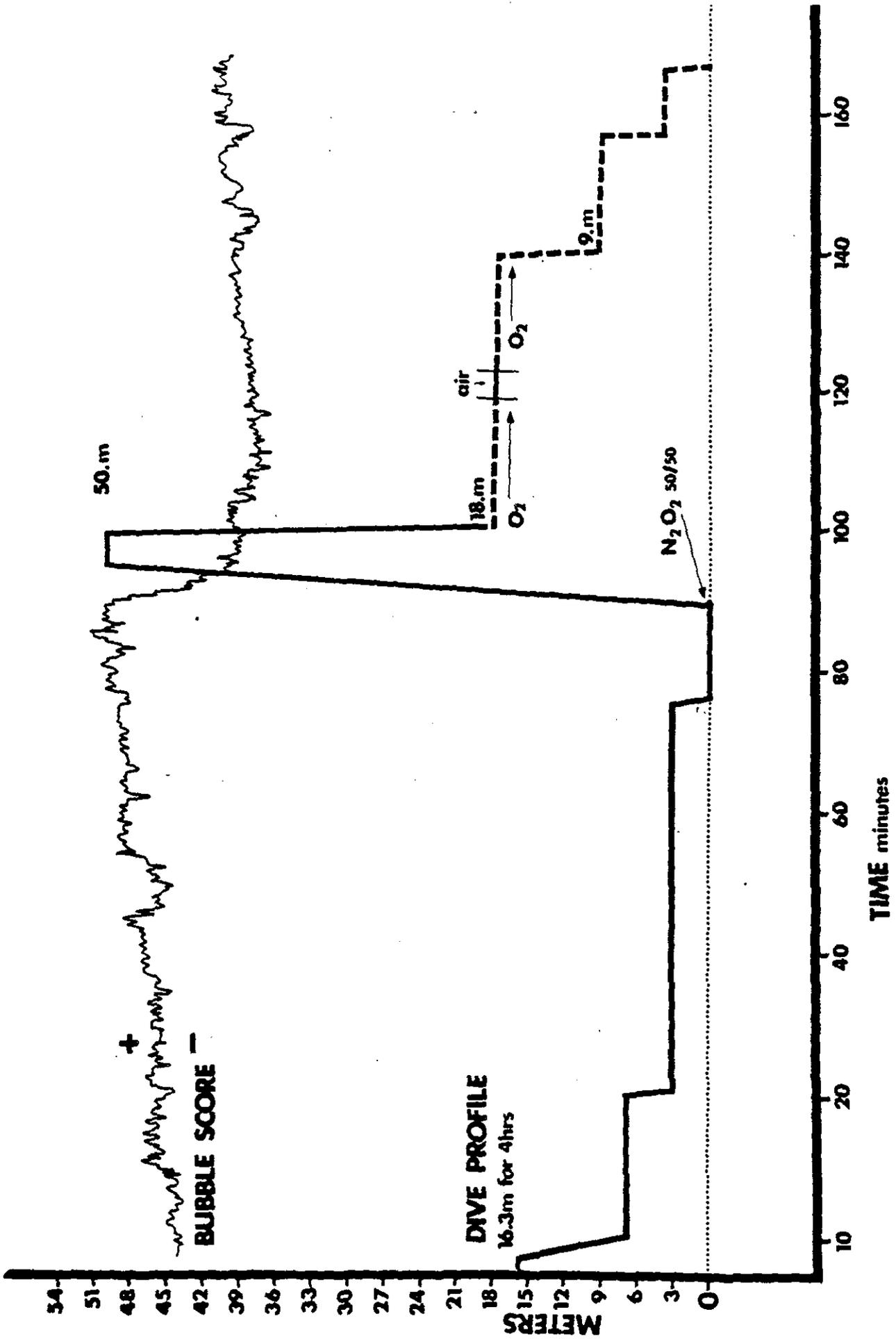


Fig. 7 - Autodec II Decompression with Bubble Formation. Recompression on 50/50 Nitrox

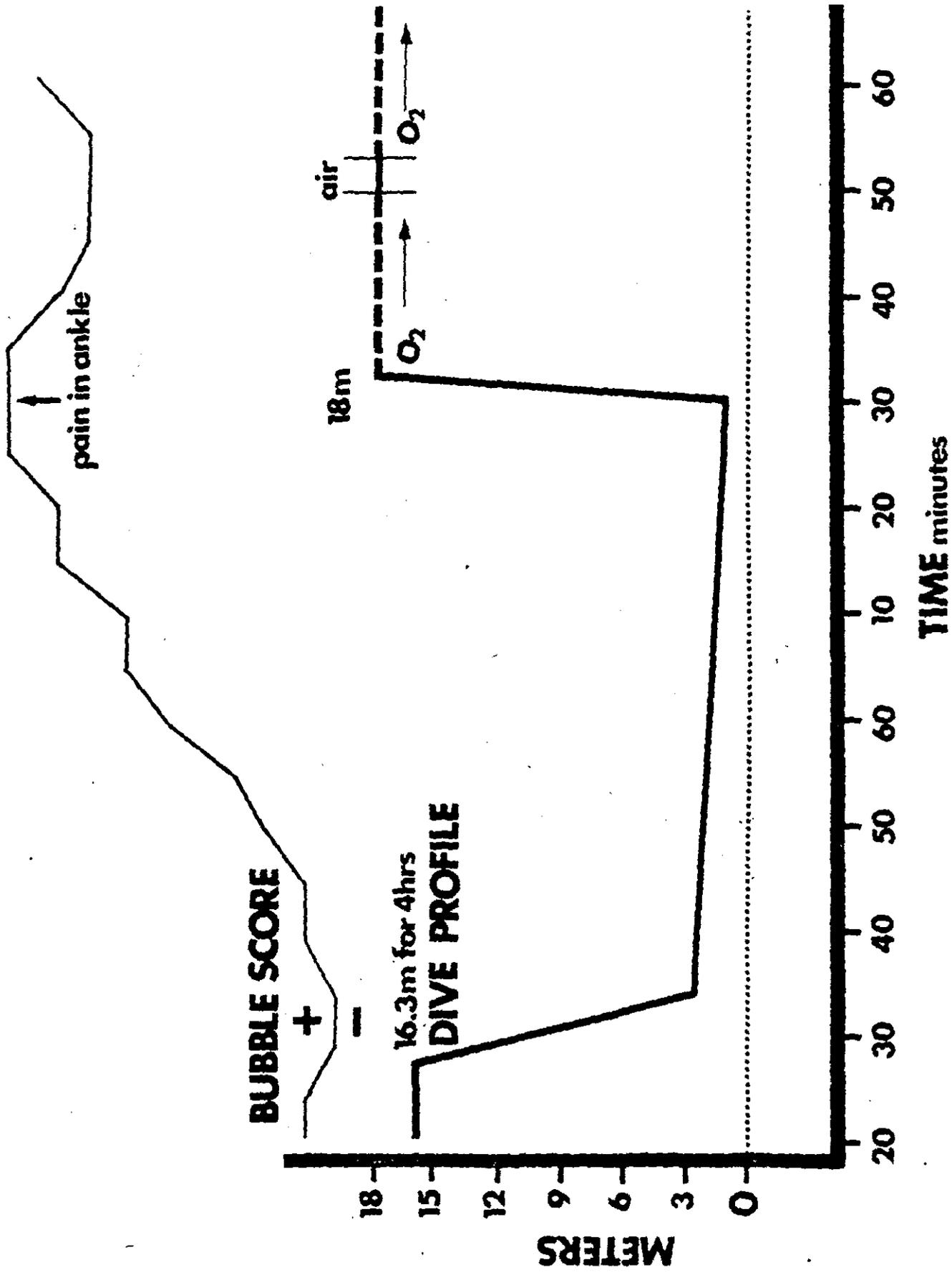
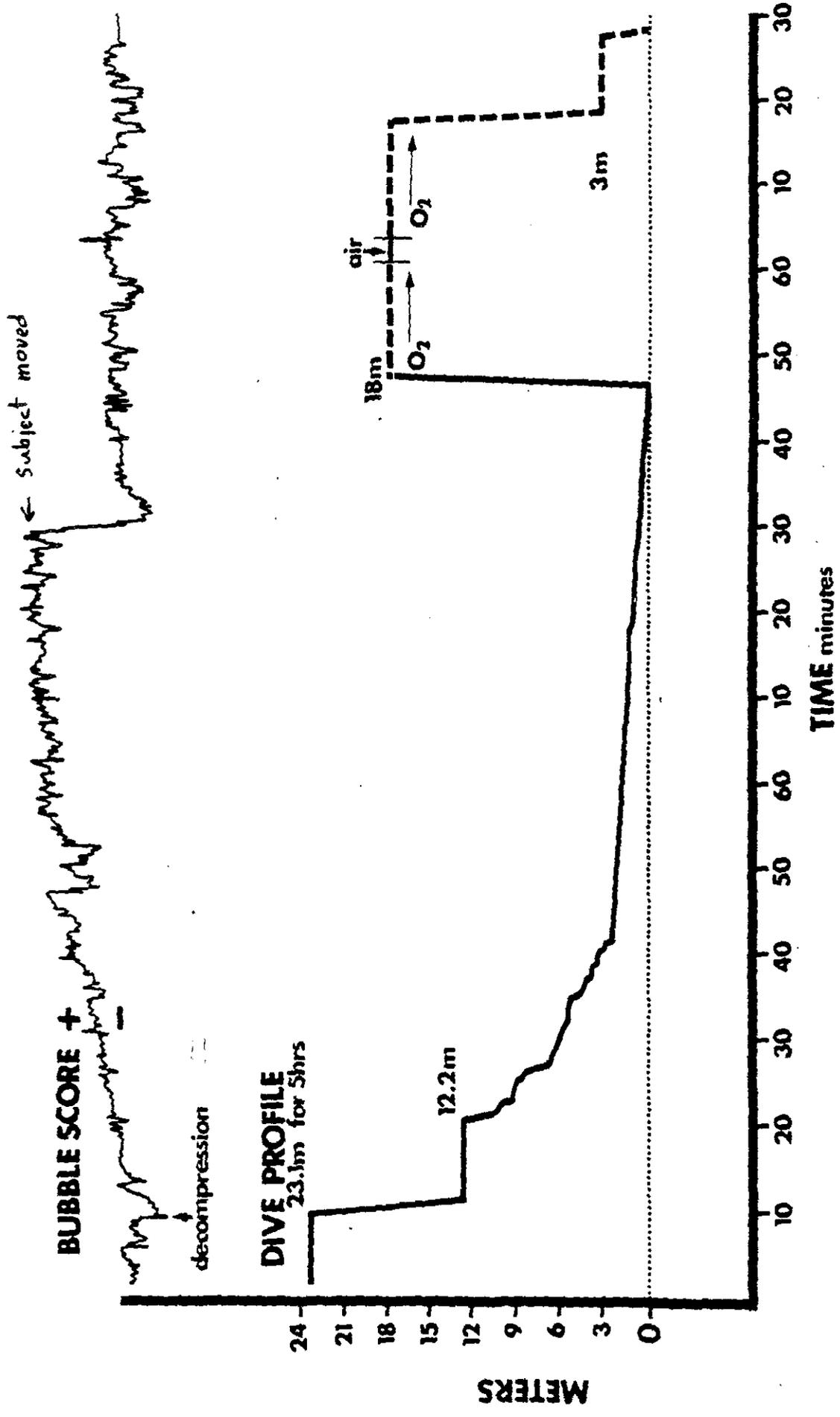
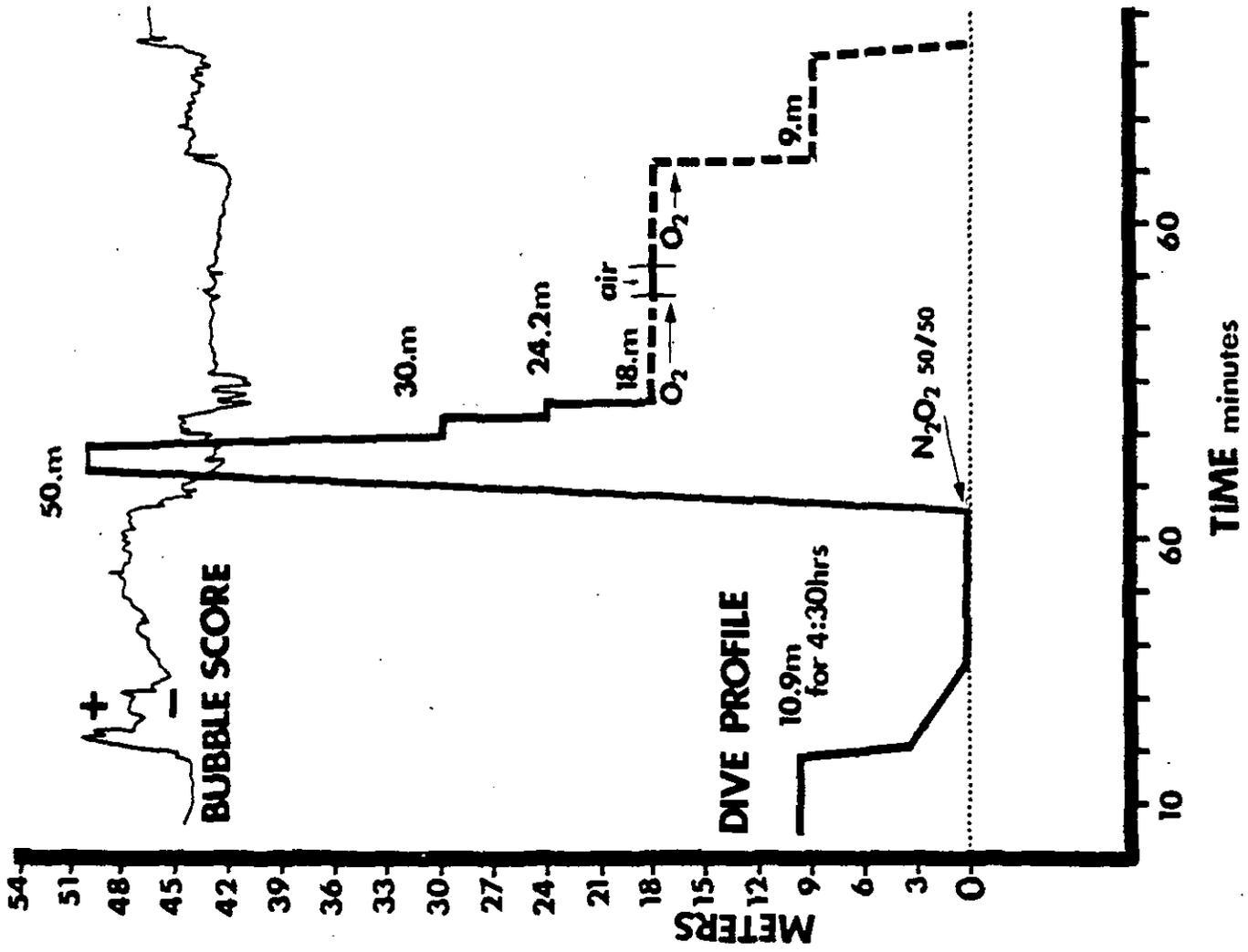


Fig. 8 - Bubble Formation Coinciding with Pain.



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Fig. 9 - Bubble Score Lost When Subject Moves.



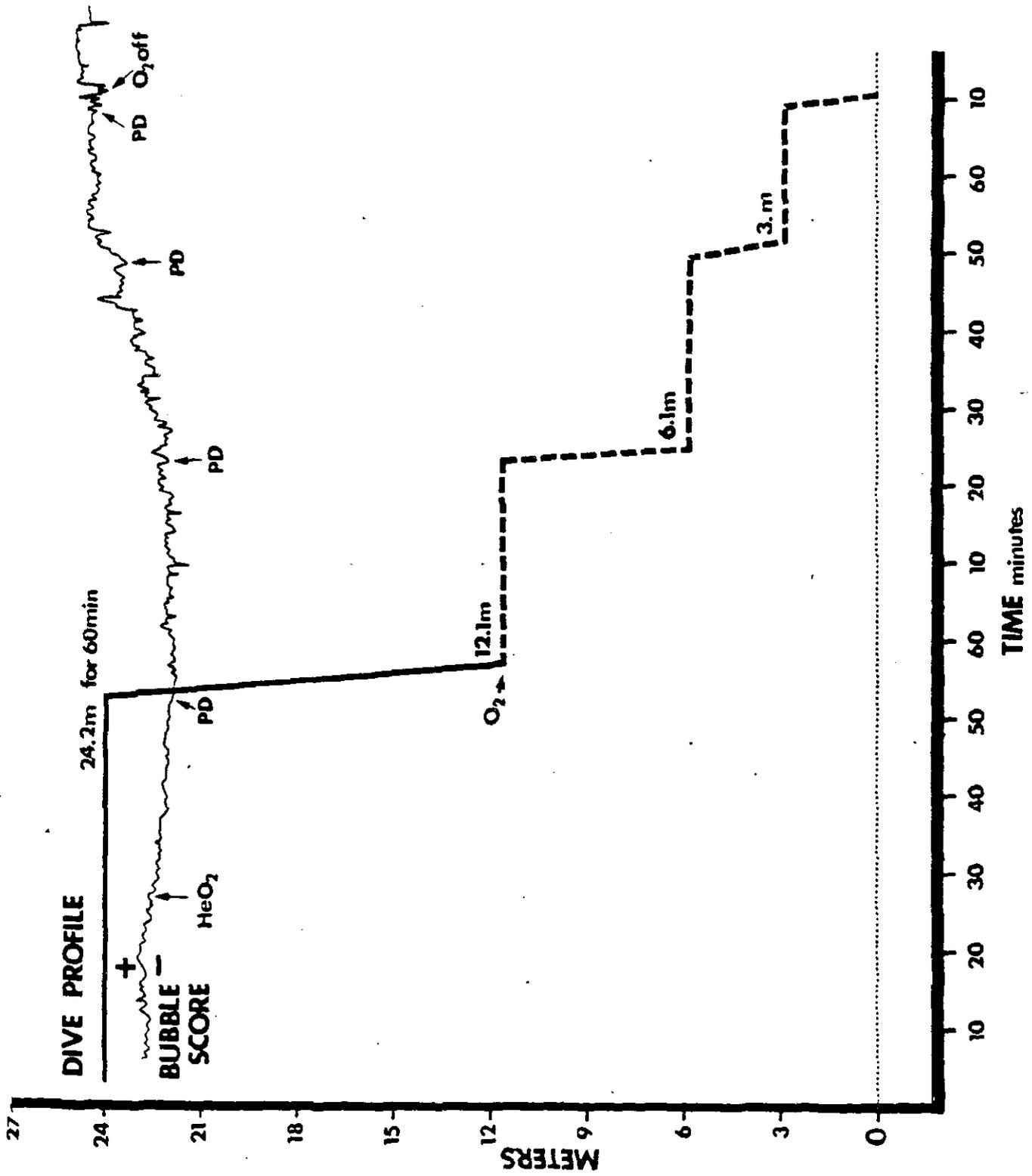


Fig. 11 - Isobaric Shift to Heliox (80/20) Produces no Bubbles.

NITROGEN ELIMINATION OVER TIME
SUBJECT A

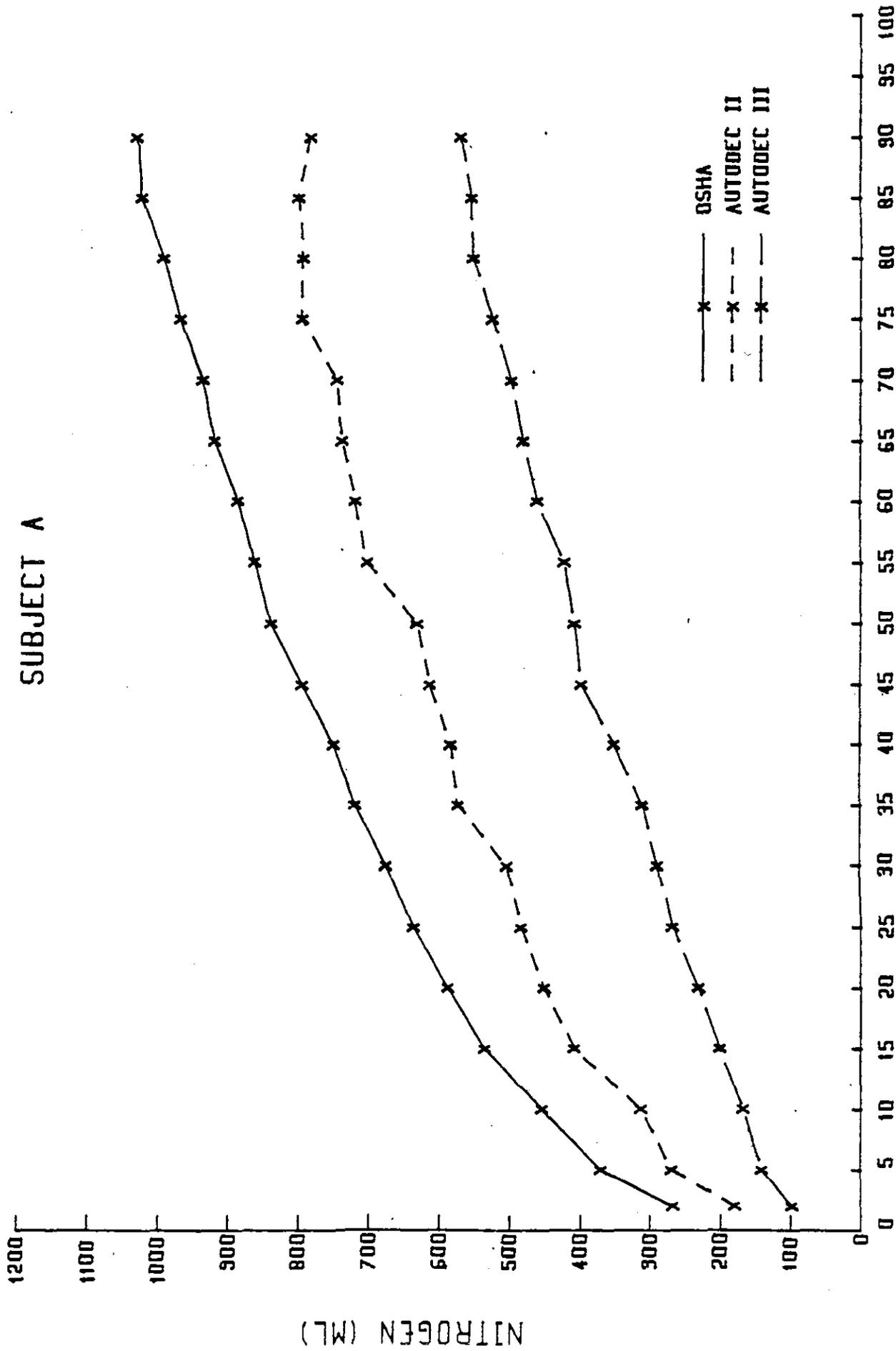


Fig. 12

-101-

NITROGEN ELIMINATION OVER TIME
SUBJECT B

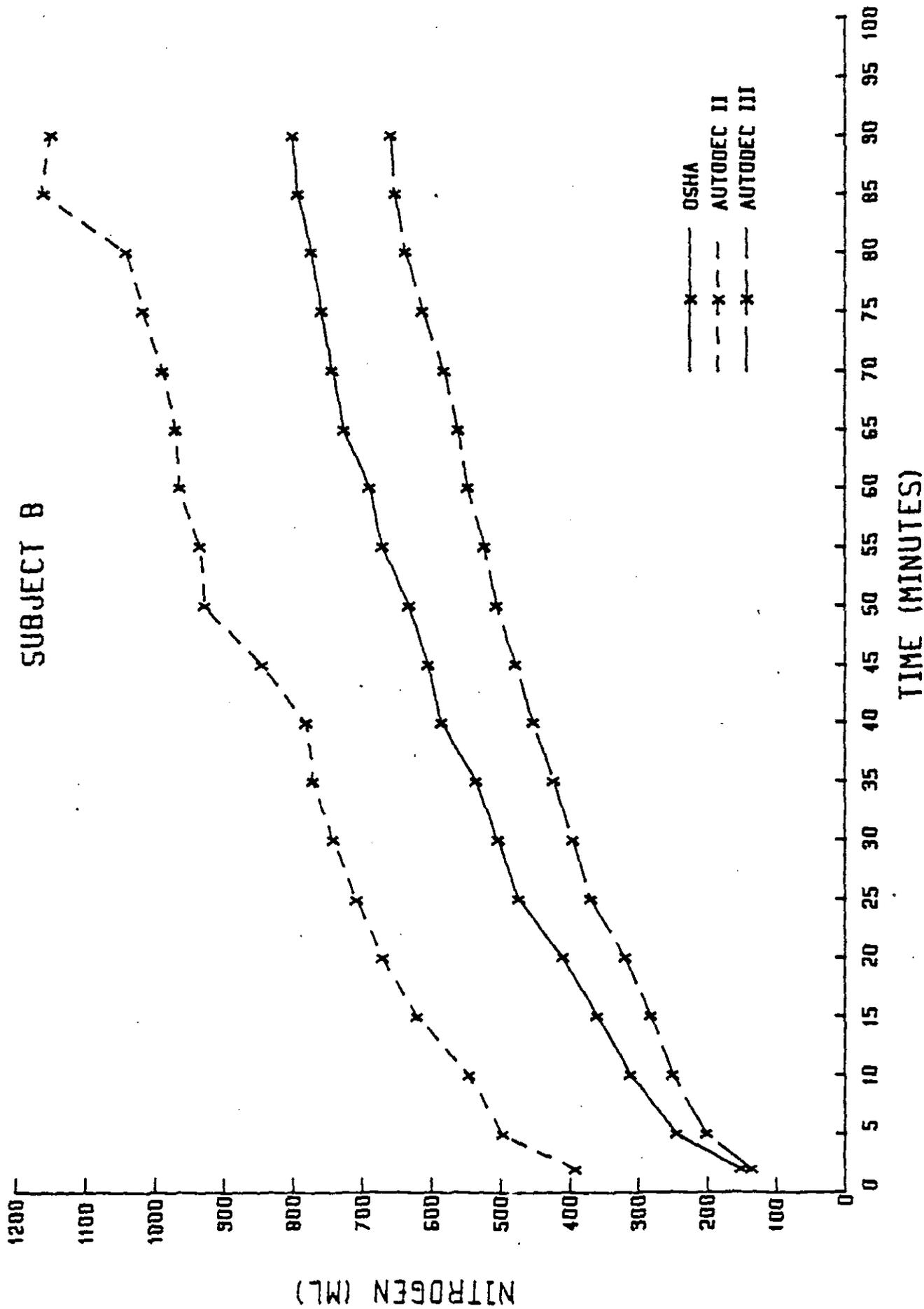


Fig. 13

102

NITROGEN ELIMINATION OVER TIME

SUBJECT D

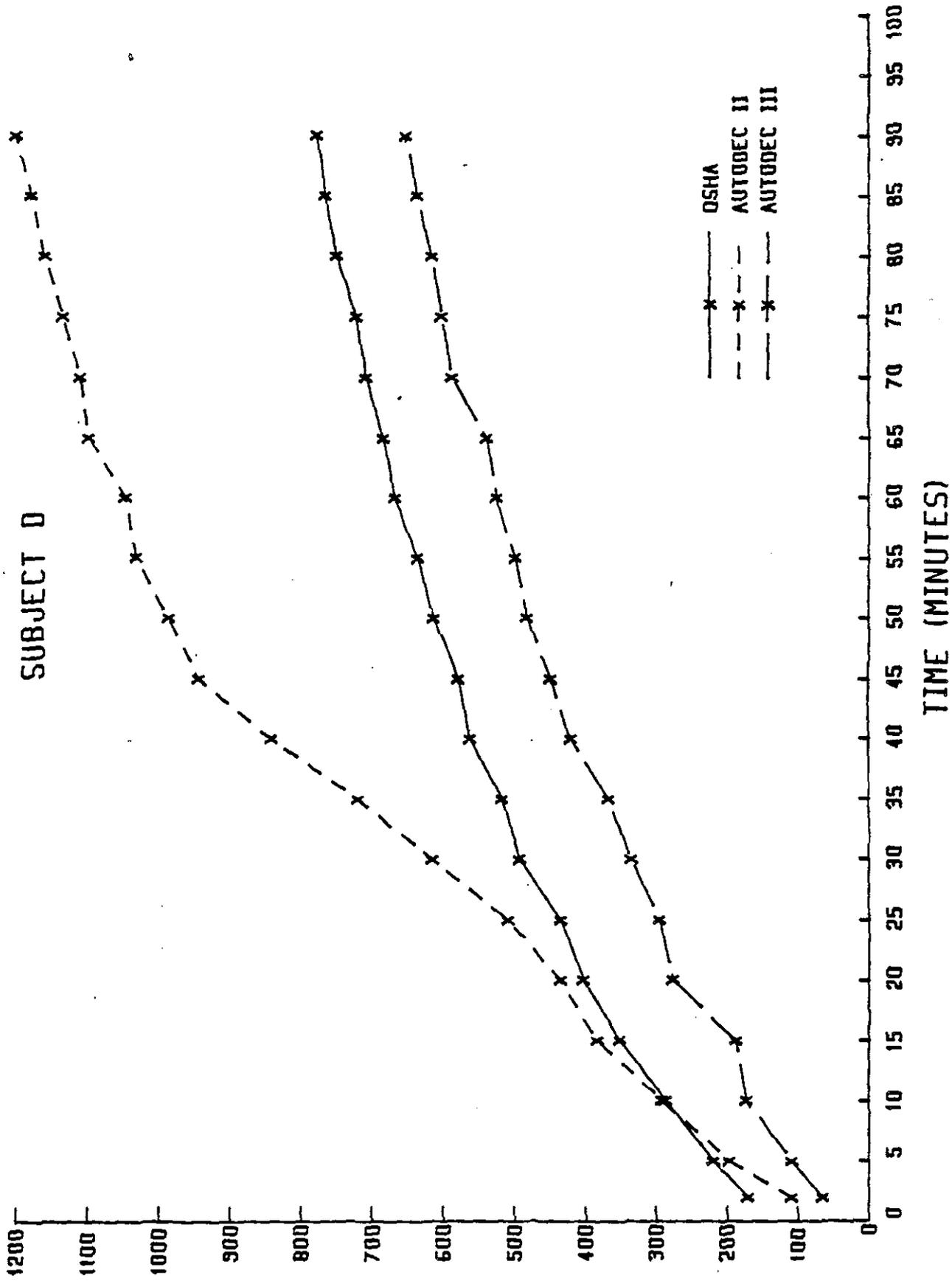


Fig. 15

108

NITROGEN ELIMINATION OVER TIME
SUBJECT E

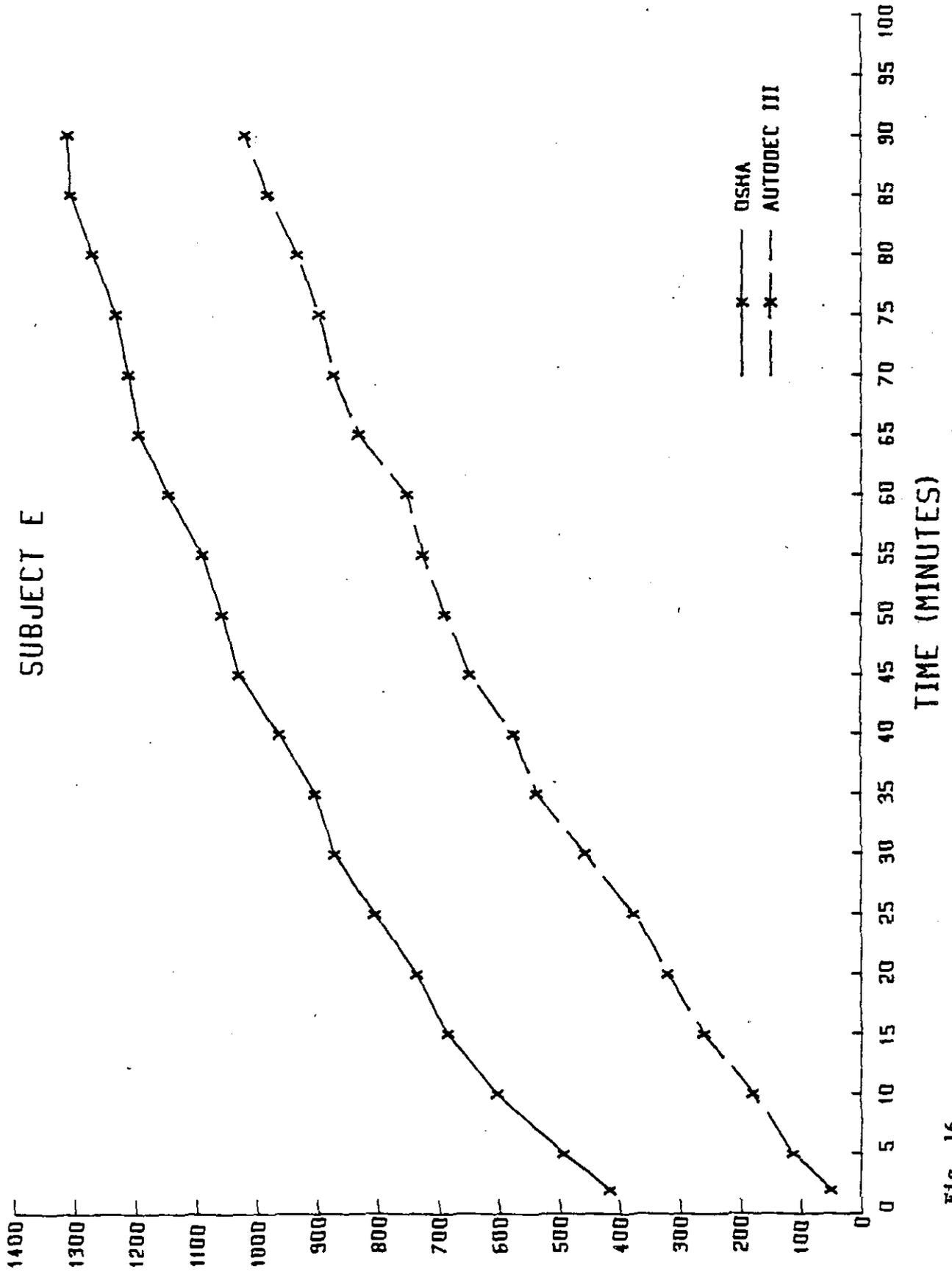


Fig. 16

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NITROGEN ELIMINATION OVER TIME
SUBJECT F

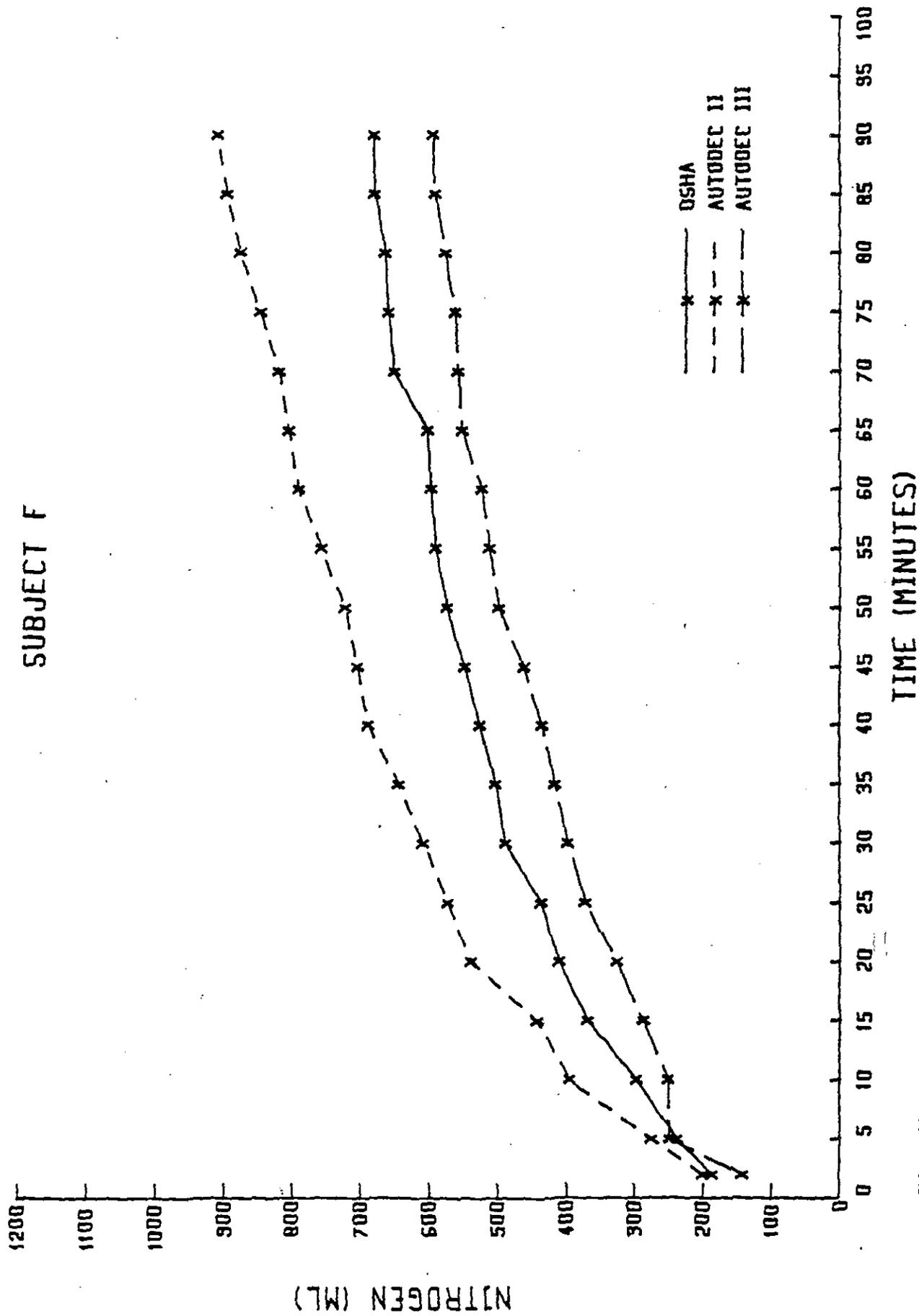


Fig. 17

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INSTRUCTIONS TO COMPRESSED AIR TUNNEL WORKERS

Compressed air tunneling or caisson construction is a successful technique that has been used since about 1840 for mining and other underground projects throughout the world. It has also been used for constructing tunnels and bridge foundations. However, most workers having had no previous practical experience with it are unclear about its uses in tunneling.

The principle behind the use of compressed air in tunneling is quite straightforward. Whenever a tunnel is being driven in soft ground containing a large amount of suspended water, due to a high water table or due to location near a large body of water such as a river, the excavation will begin to fill with water that seeps through the walls and face of the tunnel. Additionally, the ground may be so wet that it will not stand up on its own, making it difficult or impossible to mine at the face. Increasing the air pressure within an enclosed tunnel will force water out of the soil in the tunnel's immediate area thereby "drying" the face with an invisible wall of pressurized air and allowing the muck to be mined and shoveled into the muck carts. Also, air pressure pushing on the circular walls of the tunnel tends to support the tunnel, thereby eliminating the chance for cave-in prior to concreting the walls. Naturally, the air pressure required to dry a tunnel varies from job to job.

At pressures less than 17 psig, aseptic necrosis of the bone or "bone rot" has not caused a problem. However, decompression sickness or "the bends" could conceivably occur in a small percentage of tunnelers even at lower pressures. For this reason, special attention has been paid to the decompression schedules which you will use, and all decompressions will be carried out in strict accordance with

the latest recommendations of the National Institute of Occupational Safety and Health and the Occupational Safety and Health Administration.

Your company, in close cooperation with the above mentioned agencies and with specialized hyperbaric medical consultants, has carefully examined all aspects of this project to be sure that there will be adequate and appropriate safeguards for your safety at all times, particularly when oxygen decompression is in use. In the final analysis, however, the safety record for any construction project ultimately is your own responsibility. By strict observance of the rules and understanding the reasons for them, you can insure that this job like any other can be carried out in complete safety.

Because you will be working in compressed air, OSHA and your company feel that the following information will be helpful to you:

1. Leave smoking materials in the changing shack. Hydraulic oil is flammable and should a fire start in the closed environment of the tunnel, it could cause extensive damage and a shutdown of the job which would lay you off work. Also, because the air is thicker in the tunnel due to compression, heat is conducted down cigarettes so that they become too hot to hold as they get shorter. CIGARETTES, CIGARS, PIPES, MATCHES AND LIGHTERS ARE STRICTLY PROHIBITED FROM BEING TAKEN INTO THE TUNNEL OR DECOMPRESSION LOCK.
2. Do not bring thermos bottles in your lunch box unless you

loosen the cork during compression. If you do not do this, the cork will be forced deep into the thermos bottle. During compression, the cork must also be loosened so that the bottle does not explode. Very fragile glass thermos bottles might implode when pressure is applied, even if the cork is loose. When the airlock door has been closed and pressure is applied, you will notice that the air in the airlock gets warm. This is called the "heat of compression" and is normal. Once the pressure stops changing, the heat will dissipate and the temperature will return to normal. During compression, the first thing you will notice is a fullness of your ears and unless you "clear your ears" by swallowing, yawning or holding your nose and trying to "blow the air out through your ears", you will experience ear pain during compression. Once you have reached maximum pressure, there will be no further problems with your ears for the remainder of the shift. Sometimes, stretching your neck away from the affected side where pain is occurring, can help clear the ears as you swallow. When the nose is held, it must be held tightly and you must blow very forcefully with your mouth closed to equalize your ears. The reason your ears may not equalize easily is that the middle part of the ear structure in your head has a very small opening to the throat on the inner end of a connecting tube called the Eustachean tube. If

this slit-like opening is blocked, air pressure pushes on the eardrum causing pain. If air can be admitted through the Eustachean tube to the middle ear from the back of your throat, the pressure is equalized and no pain occurs. Should you experience pain during compression, notify the foreman immediately so that compression can be stopped until you have managed to clear your ears. Sometimes reducing the pressure a couple of pounds will allow the ears to clear and then pressure may be safely applied again to reach the pressure in the heading. Trying to force the ear when it will not equalize or trying to "tough it out" may result in a broken eardrum. During decompression your ears may pop and squeak but it is not necessary and indeed, it is forbidden to hold your breath and blow into your ears. The air escapes from the middle ear very easily during decompression and needs no help although it may be noticeable by the clicks, pops and squeaks.

4. Should you experience buzzing in your ears, ringing in your ears, or deafness following decompression which persists for more than a few hours, you must report to the compressed air physician for evaluation. Under extremely severe but rare conditions, a portion of the middle ear structure other than the eardrum may be affected if you have had a great deal of difficulty clearing your ears and in that case this must be

surgically corrected within two or three days to avoid permanent difficulty.

5. Other areas of the body which contain air are the sinuses of the face and head. These are pockets of air inside the bones of the face and in the middle of the head which normally communicate through the nose to the outside. As long as the openings to the sinuses are not blocked by swelling or mucus, they cause no problem. If they are blocked, you may experience pain over either or both eyes, in the cheeks or if the one in the center of the head is involved, the pain will radiate to the back of the head. There is little you can do immediately if a sinus is blocked other than take your time compressing or use a decongestant nasal spray. Sometimes, a "sinus squeeze" caused by compression will cause you to spit out blood which comes from the back of your nose. This occasionally is not even associated with much pain and is of no serious consequence.
6. If you have trouble equalizing your ears or sinuses, it is sometimes helpful to take decongestant tablets or capsules which can be bought at any drug store. They are often used by cold and hay fever sufferers. If difficulty persists, with pain in the sinuses or the ears while compressing each day, see the compressed air physician as he may be able to suggest other means to take care of this problem.

7. If you have a cold or an attack of hay fever, it is best not to try compressing in the air lock until you are over it. Colds tend to make it difficult or impossible for you to equalize your ears or sinuses.
8. Very occasionally, some people experience pain in a filled tooth. This may happen if there is air under a filling, and it cannot easily equalize. If you explain this problem to your dentist, he can repair it. Unfilled teeth even with bad cavities in them rarely if ever, present problems.
9. False teeth and contact lenses as well as regular glasses, can be worn with perfect safety in the compressed air environment.
10. Should anybody sustain a severe injury to his chest, back or rib cage while working at pressure in the tunnel, special care must be exercised before and during decompression. If the victim has a broken rib which has punctured the lung, air can leak out of the lung and collapse the good lung as it expands inside the rib cage during decompression. Anyone suspected of having such an injury should be examined by the compressed air physician before he is decompressed and should only be decompressed under his supervision.
11. During decompression, the air in the manlock will become cold and this is known as the "chilling of decompression" which is entirely normal. Fog may form in the chamber. Again, the temperature will return to normal and the fog will disappear as soon

as the pressure stops changing when you reach the surface.

12. It is very important that you breathe normally during decompression and not hold your breath for any reason. This is because the air must freely exchange in and out of your lungs to avoid air trapping in the lungs. Should this occur, the lungs will overexpand and theoretically could rupture with the possibility that air could be forced into your bloodstream with very serious consequences to your brain. This kind of disorder is called air embolism and while experienced by divers, it has never been truly proven to happen in tunnel workers. Nevertheless, you should be aware of this theoretical possibility and its symptoms. These could include unconsciousness, paralysis of one side of the body, or one pupil may appear to be bigger than the other. These symptoms, should they ever appear, would come on immediately (within seconds) after the decompression is completed and there is no possibility of their occurring later. Should anyone ever experience collapse on leaving the chamber, he should be immediately recompressed to 60 feet breathing oxygen in the emergency medical lock located topside and the physician must be notified.
13. Because compressed air is used on this job, an employee must take proper decompression every time he locks out during or at the end of a shift. Each decompression must be in accordance with the officially approved decompression schedule posted on the inside of the combination lock. Also, everytime an employee enters or

leaves the compressed air environment, he must be registered in the special log book which is kept by the lock tender. No employee may undergo more than one decompression within any 12 hour period.

14. Avoid taking round faced watches into the working chamber unless they are definitely labeled to be pressure-proof. Sometimes, compressed air can leak into a "water resistant" watch and then during decompression when the air inside the watch expands, the crystal will pop out. Square faced watches are usually leaky enough so that this does not happen.
15. Should you experience any kind of discomfort at any time during or following decompression, you must notify the supervisor immediately so that a medical evaluation may be made. If you were to develop signs or symptoms of decompression sickness, early treatment will greatly shorten treatment times and reduce your discomfort. Also, it is important that all cases of decompression sickness be reported so that the safety and efficacy of the decompression tables can be continuously monitored.

I hereby certify that I have carefully read the above information or have had it read to me and that I have been allowed sufficient time to study and fully understand it.

Date: _____

Signed: _____

Name: (Print) _____

APPENDIX XV

Sonic Tissue Imaging of Fixed Bubbles

ULTRASONIC DETECTION OF STATIONARY BUBBLES IN ASYMPTOMATIC HUMANS *

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INTRODUCTION

The technique to detect stationary tissue bubbles during and following decompression using ultrasound tissue imaging was first conceived by MacKay² in 1963 and later put into successful practice by MacKay and Rubissow³. These studies were done for the most part in small animals decompressed from depths as great as 13 atmospheres. In this project, we hoped that we could demonstrate the formation of decompression bubbles before they produced symptoms in human beings.

Methods

After discussion with co-investigator Melton, a specialist in ultrasonics, the ADR ultrasonic tissue imager operating at a frequency of 5 MHz was selected. The ultrasonic scanner was connected to a strip chart recorder using a signal processor which had as its function to take the video signal as it was delivered to the CRT screen and integrate the changes in the image elements so that they could be displayed as a single line chart recording. Initially it was not known whether the appearance of bubbles would lead to an increase in the number of image elements contained in scans of the selected tissues or whether there would be an increase in the strength of image elements

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contained in scans of the selected tissues. Depending on which hypothesis was true, a suitable integrator had to be built. Initially, the integrator was constructed to detect an increase in the number of image elements contained in the scan.

Transponder placement

The placement of the scan head was the next problem to solve. Motion of the subjects which would displace the scan head even slightly during the course of an experiment could severely alter the readings. We did studies in vitro with chunks of meat which had been saturated at high atmospheric pressure and then decompressed with the scan head coupled to the surface of the meat using a water coupling. We felt that bubbles could be detected in nonviable meat. Therefore, we turned our attention to assessing various methods of placing the scan head on the human. The Oxford group (Daniels et al)¹ had previously used the ADR machine strapping the scan head to the antero-medial thigh but we found this method too unstable to generate reproducible data. We tried applying the transducer directly to the skin and then we also built a water-filled plastic standoff with a thin rubber diaphragm closing it where it rested on the skin to avoid possible blanking out of the electronics by bubbles appearing within the first centimeter.

Experiments were also carried out using a water bath coupling in which the arm was immersed but this proved too tiring to the subject even when a cast was applied to keep the arm steady. Bubbles in the water also produced artifact and we found that bubbles also appeared on the skin surface. The subscapular fat pad was unacceptable as respiratory movement produced artifact.

Finally, we analyzed the cases of decompression sickness in tunnel workers previously treated at this facility and discovered that the vast majority suffered symptoms in the lower limbs from the knees down. Therefore we made individual bivalved fiberglass casts for each subject in which a window was cut over the gastrocnemius muscle. The probe, with water-filled standoff was applied to the skin through this window with a mineral oil coupling. This produced a steady baseline and was tolerable over long periods to the subject. The transducer was clamped to a steel post affixed directly to the cast adjacent to the window to avoid movement. Care was taken so that the skin contact pressure was low as we felt that excessive contact pressure might prevent bubble formation during decompression in the underlying tissues.

Integrator

After the positioning of the transducer seemed adequate, we still got mixed results and turned our attention once again to the integrator. Two new integrator designs were made for true integrating bubble counters. One design utilized integration followed by sample and hold and the other design utilized a more

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slowly relaxing integrator in which case a sample and hold was not needed. The latter design worked better. The sample and hold devices were not capable of holding the integrated image elements of values with sufficient stability whereas the slowly relaxing integrator operated with the requisite stability (holding time of 1 microsecond, relaxing time of 5 seconds).

Even with the new instrument which should definitely have been able to detect bubbles, results were still mixed and ambiguous. In a critical experiment, one of our laboratory staff members volunteered to be decompressed after a four hour exposure at 16.3M (54 ft.), directly to the surface. He was held on the surface for 13 minutes while careful recordings were made to detect bubble formation. There is no question that bubbles would be generated under these circumstances. After 13 minutes, the subject was recompressed to 18M (60 ft.) and placed on oxygen. He suffered no overt symptoms and the safety of this experiment was based on previous work of one of the co-investigators. During the 13 minute surface interval, no bubbles were recorded using the 5 MHz ultrasound machine. Thus, it seemed that the hypothesis tested negative.

Frequency

At that time we noted that the original work carried out by MacKay in 1963 used 7.5 MHz. When we had originally purchased the ADR 5 MHz scanner, we were told by the company that the 7.5 MHz scanner head would soon become available. However, after the equipment had been delivered the company cancelled plans to market a 7.5 MHz transponder. Therefore, after 8 months experimentation with the 5 MHz apparatus, we chose to go to a higher frequency of ultrasound so that backscatter from small bubbles in tissues could be increased above the level of backscatter due to mechanical discontinuities normally present in the tissues. Consequently, further experiments were carried out with other equipment at 7.5 and 15 MHz. However, these experiments failed to yield consistent results. By July of 1982, we had concluded that ultrasonic tissue imaging of stationary bubbles was not possible in asymptomatic human beings at least using the equipment we had. At that time we had concluded that if small bubbles were to be detected in muscle, the frequency had to be greater than approximately 16 MHz for bubbles of approximately 5 MHz diameter. This calculation was consistent with our findings to that time with decompression bubbles in vivo.

Threshold

During the summer of 1982 Dr. Melton continued working on determining the correct threshold for detecting bubbles against tissue backscatter background. By measuring the sonic reflection from individual bubbles produced electrolytically, and also measuring baseline gastrocnemius muscle backscatter in vivo as well

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as cardiac muscle backscatter in vitro, it was determined that backscatter from muscle is of the order of 10 times larger than backscatter from isolated bubbles of less than 5 microns. By September of 1982 it became clear that we had set our threshold for detection of bubbles of the order of 20 to 30 times too high and that the integrator had to be further modified. Thus, with the threshold set quite low, although it was feared it might be too sensitive, 4 possible baseline settings were contemplated. These correspond to the region of backscatter amplitudes where bubble scattering is located.

The measured average backscatter for muscle was approximately -50 db (normalized to a perfect reflector) whereas the measured average backscatter for isolated bubbles of 40-50 μm diameter was approximately -60 db. The above measurements were made using 5 MHz operating frequency (nominal). From the measurements the average normalized backscatter from isolated bubbles of 2-5 μm diameter was estimated to be between -70 db and -80 db.

These results indicated to us that ultrasonic detection of small, isolated bubbles in vivo within soft tissues cannot be readily perceived in B-scan images because of the inherent ultrasonic speckle. The basic difficulty that this raises is that the spatial pattern depicted in a B-scan is not congruent with the spatial pattern of fundamental acoustic properties of the object. The detected rf envelope takes on a Rayleigh distribution for scatterers. Thus bubbles could not be seen on the CRT screen but they could be detected electronically. Final modifications were made to the integrator.

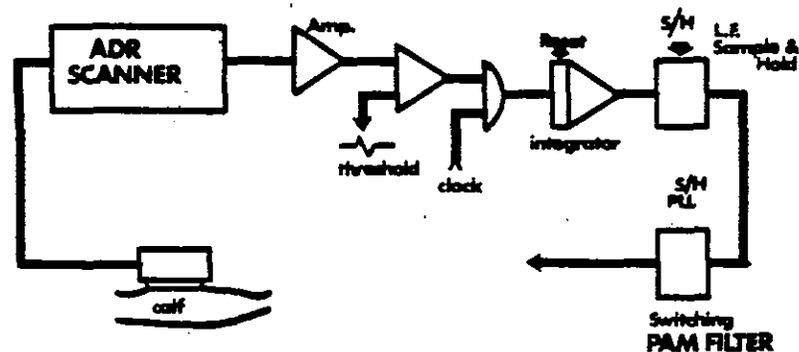


Fig.1 Circuit diagram of electronics.

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In October of 1982, we set the baseline for the most sensitive setting and on October 29th, the first test was made. Since we had not had time to establish a formal baseline, we presumed that the drift we saw (in the direction of bubble formation) was simply baseline drift. Later, after a second experiment was carried out with a steady baseline present it was discovered that the deviation of the chart recorder print was indeed due to bubbles.

Seven human subjects were exposed to pressures from the equivalent of 11 meters to 50 meters of seawater for periods which ranged from 20 minutes to 5.5 hours. Twelve experimental trials were made from which satisfactory recordings could be obtained. With the ultrasonic transducer (without the water-filled stand-off) affixed to the right calf of each subject, with movement minimized by the full length plastic leg cast, a baseline was usually established on the recording graph for 15 to 30 minutes before decompression began.

It is calculated that the instrument is able to detect bubbles of two microns size or larger or clusters of bubbles. The tissue slice interrogated measures 7 cm in depth by 5 cm in length by 2 mm in width.

RESULTS

Below are representative graphs showing bubble formation during decompression and the suppression of bubbles with recompression.

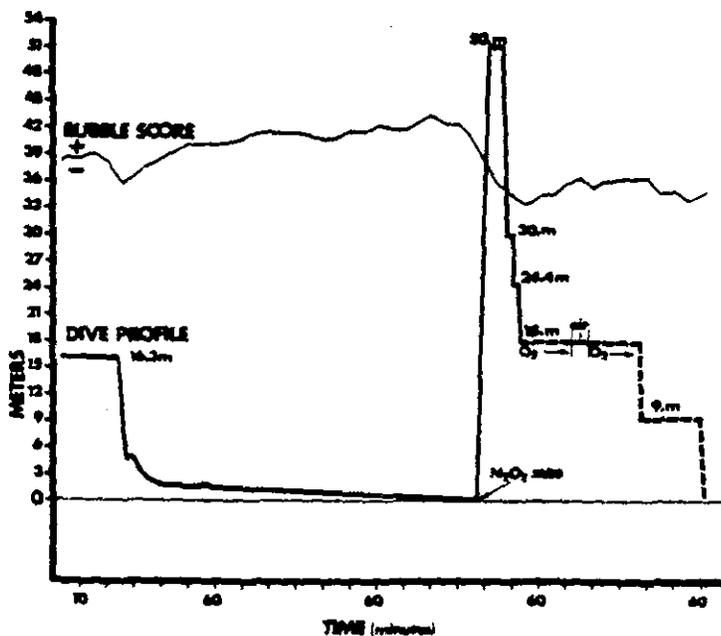


Fig.2 Exposure at 16.3M for 4 hrs. 50M re-dive after surfacing.

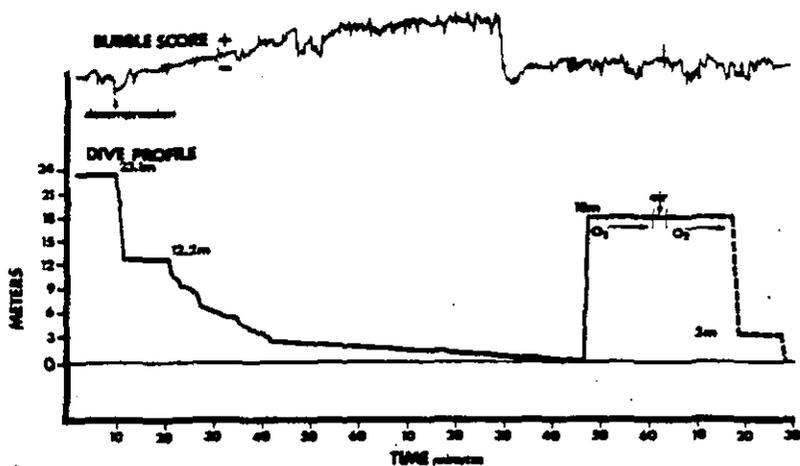


Fig.3 Exposure to 23.1M for 5 hrs. Bubbles disappear on movement.

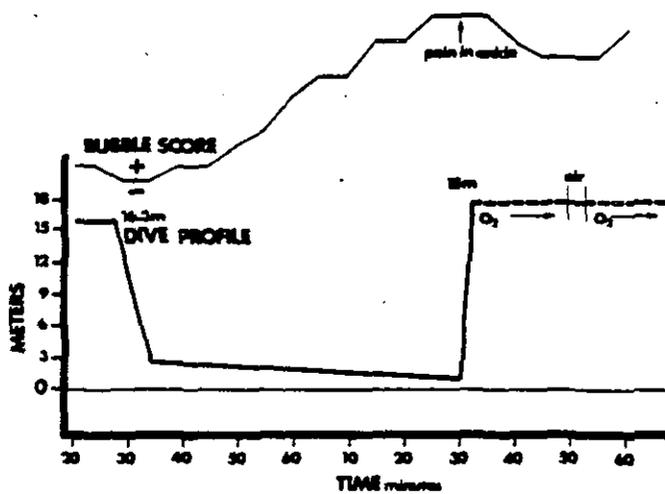


Fig.4 Exposure to 16.3M for 4 hrs. Re-dived on O_2 after surfacing

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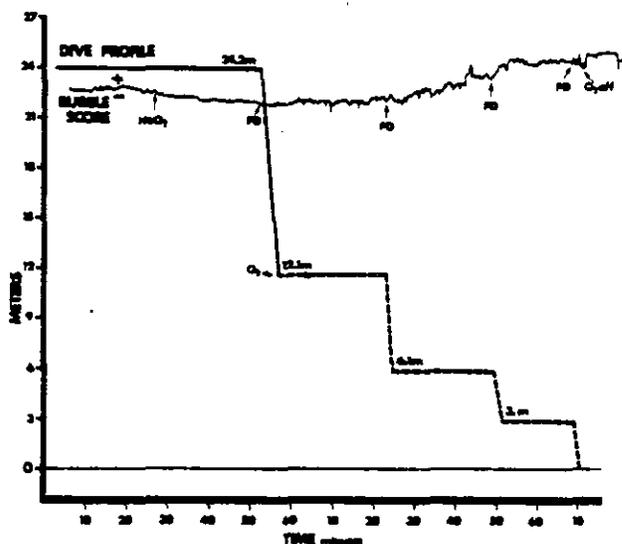


Fig.5 Isobaric shift from air to HeO₂ at 24.2M.

Bubbles were uniformly recorded on decompressions from all pressures tested when the exposure time had been greater than one hour. Bubbles could not be detected in short half-time tissues after shorter exposures even following dives to 50 meters.

We now feel that we can demonstrate bubbles appearing immediately as decompression commences and continue to grow and that these bubbles are diminished on recompression. We also ran studies on 2 occasions shifting the patient to helium isobarically at depths of 24.2M (80 ft.) and 50M (165 ft.). On neither occasion did we detect bubbles following the isobaric shift to helium from air. However, as we decompressed from these pressures, bubbles appeared. (Figure 4)

In summary, we feel we have developed a method for detecting stationary bubbles in asymptomatic humans. The present drawbacks or limitations are several: 1. transducer movement must be absolutely avoided or the results cannot be reproduced. 2. any movement of the subject during the course of the scanning may result in the sudden dislodging or disappearance of bubbles as detected by the scanner. 3. at the present state of development we cannot quantitate or discern the severity of bubble formation or relate the rate of increase in bubbles to the severity of the decompression. Further work will have to be carried out to refine this technique enabling us to use it for monitoring of decompression under practical conditions or make it useful in the development of decompression tables.

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