8

Medical Advances in Compressed Air Construction Work

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I. INTRODUCTION

Caisson and compressed air tunnel exposures are different from those seen in diving in several important ways. Caisson work is invariably carried out at very modest pressures never exceeding the equivalent of 34 meters (112 feet) of sea water or 50 pounds per square inch. Bottom times or shift lengths, however, almost always range between 4 and 8 hr on a daily basis with 6 to 8 hr exposures being the most common. Furthermore every caisson exposure completely fills the envelope covered by the decompression schedule in use. A new schedule is provided for every additional 1 to 1.5 meters equivalent seawater depth. This is done for economic reasons as a pound or two difference would mean a new schedule and contractors with large gangs of men need to minimize decompression time. Thus, approximately 4 out 5 caisson exposures will test the table to its limit whereas only about 3 in 10 water dives pushes the table to a similar extent. Diving tables are invariably set up in 3 meter increments.

Caisson workers also work in a dry environment and thus must support the weight of their own bodies throughout the exposure as well as the tools and the burdens which they carry. The atmosphere in the tunnel frequently has more contaminants than are present in the divers air supply. Tunnelers are rarely chilled during the exposure but may be exposed to excessive heat during concrete pours. Chilling takes place during decompression when they are seated in a dry chamber. Balldin has demonstrated that there is 30% less nitrogen elimination in those decompressing in the dry as opposed to those decompressing while immersed (Balldin and Lundgren, 1969). Finally, caisson exposures are much more numerous than diving exposures. At the present time some 236,000 man-decompressions are being analyzed which were carried out using the Blackpool caisson schedules (Evans, 1987). Despite the great amount of material available for analysis, there has been relatively little study or scholarly work invested in caisson tables as opposed to those for deep sea divers. Physiologists used to dealing with the diving community often assume that caisson decompression sickness data can be treated in the same manner as diving statistics. This is not true as the decompression sickness figures from caisson work are never correct as reported. Official rates deal only with treated cases of decompression sickness. This is because the men fear for their jobs if they complain of symptoms. Because caisson tables have been notoriously bad for so many years, those engaged in this kind of work accept symptoms of decompression sickness as a fact of life (Nashimoto, Personal Communication, 1987). They rarely report for treatment unless symptoms are unbearable or incapacitating. Too frequent recompression treatment would mean loss of a job. Using an anonymous system of reporting on a tunnel project in Milwaukee in 1971-72, we found that up to 26% (Kindwall, 1975) of a shift might be bent on any given day and that we had decompression sickness present on the job on 42.5% of the working days. This was despite the fact that our "official" decompression sickness incidence was 1.44%.

II. DECOMPRESSION PROCEDURES

Traditional caisson decompression was accomplished by simply opening the valve to the manlock at the end of each shift and bleeding off pressure in a continuous manner. Stage decompression was unknown. There was a 25% mortality among the workers building the Hudson tubes which dropped to 4% with the introduction of a recompression treatment chamber. Knowing that shorter exposures seemed to decrease the incidence of decompression sickness, the concept of the split shift arose. This meant that instead of one continuous long working period during the day, the workmen would work a relatively short shift in the morning, followed by a rest period on the surface which in turn would be followed by a second shift in the afternoon. It was thought that by working two shorter shifts, the decompression sickness rate would be lower. It was not understood that the time period on the surface between the two shifts was pitifully inadequate to allow release of meaningful amounts of nitrogen. The second failing point of the split shift was that it exposed the worker to the trauma of two decompressions per day instead of just one.

In addition to devising the first set of decompression tables in 1908, Haldane also tested different decompression schemes. He found that continuous decompression, such as caisson workers used, is inferior to stage decompression causing serious symptoms or death 25 times more often than stage decompression (Boycott *et al.*, 1908). Nevertheless, in 1922 the State of New York produced a decompression code embodying not only the split shift but continuous or uniform decompression. Unfortunately the split-shift is still in use in Japan. Fig. 1 shows how the Japanese caisson schedule compares to a U.S. Navy repetitive dive for the same exposures.

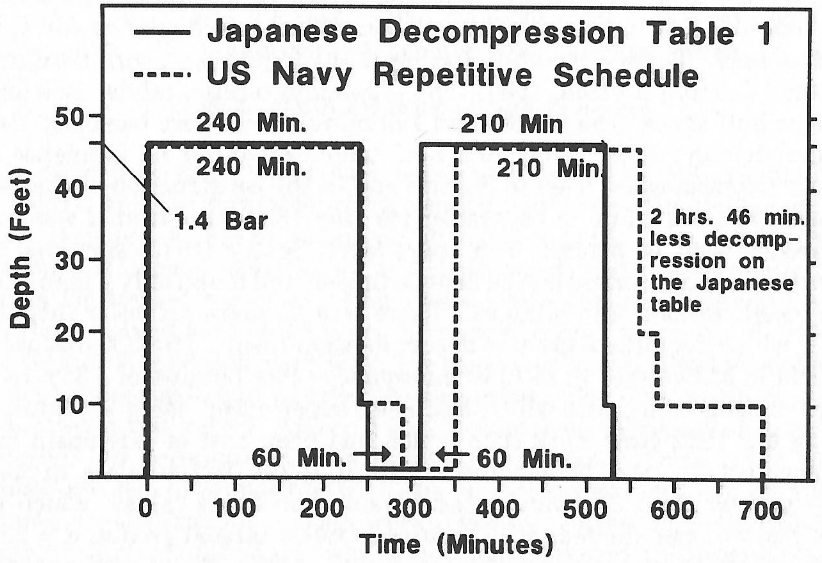

Fig. 1. Japanese caisson schedule compared to U.S. Navy dive schedule.

Aseptic necrosis was first recognized in tunnel workers in 1912 (Bornstein and Plate, 1911-12). Bone disease appears to be caused by improper decompression. Very costly human experimentation has shown that in the production of bone necrosis, decompression time is the only independent variable. Short tables produce necrosis — long tables produce less or none.

The 1922 New York table remained the gold standard of decompression in the United States until the 1960's. Beginning in 1958, the British Medical Research Council Panel on Decompression Sickness began to investigate the incidence of aseptic necrosis in tunnel workers and found a 19% incidence of bone disease in the workers building the Clyde tunnels (Jones and Behnke, 1978). The Blackpool tables were adopted in 1966 in an effort to avoid aseptic necrosis. Nevertheless, 5 of 59 workers on the Dungeness SB power station contract developed bone disease on the Blackpool tables (Trowbridge, 1977). Yau has reported that 83% of the men working on the Hong Kong Subway project reported decompression symptoms in association with the Blackpool schedules (Lam and Yau, 1988; Yau Personal Communication, 1987). The "official" bends rate however was low.

In 1963, Duffner devised the Washington State tables which later were adopted as the OSHA tables in 1971. These tables abolished split-shift, but retained continuous or uniform decompression in stages after an initial pressure drop. This was in deference to the contractors and workers who did not wish to break with tradition. When asked why he did this, Duffner said, "There are certain battles that you just can't win" (Duffner, Personal Communication, 1987). The Washington State tables used only 3 tissue half times, (the 30, 60, and 120 minute) but were basically Haldanian (Sealey, 1969). Duffner's new tables produced no incidence of aseptic necrosis when used in Seattle and in the construction of the San Francisco subway, but on this latter job only 135 feet of tunnel was dug at greater than 16 pounds. Ten years later, Sealey (1975) surveyed 83 workers who had worked on the Seattle project and found only 4 men with tibial shaft lesions, one bilateral. There was no juxta-articular involvement, which requires a greater decompression insult. These tables were adopted in Milwaukee in 1970 by emergency order because of a 35% incidence of aseptic necrosis which had been experienced using a modification of the 1922 New York code which had been part of Wisconsin law (Kindwall *et al.*, 1982, Nellen and Kindwall, 1972). Nevertheless, at pressures greater than 36 pounds, the Washington State tables (which by then had become the federally enforced OSHA tables) produced a 33% incidence of aseptic necrosis (Kindwall *et al.*, 1982). Fig. 2 compares the OSHA and Blackpool tables for the 2, 4, 6 and 8 hour exposures. Note that on the Blackpool tables, the decompression time at any given pressure is the same for any time period over 4 hr up to 8 hr. The OSHA schedule is more conservative for most long exposures between 14 and 44 psig. The lines (dashed or solid) become thicker with increasing exposure.

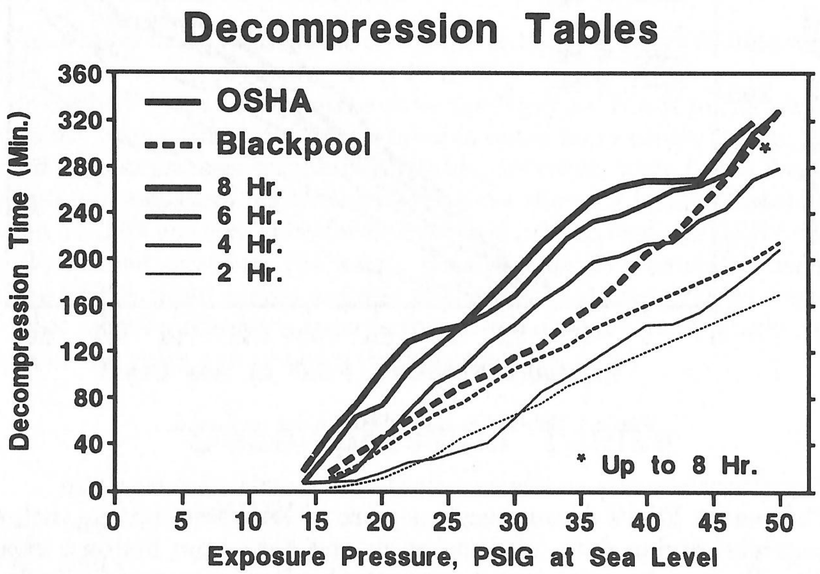

Fig. 2. OSHA and Blackpool tables compared.

In retrospect, there was a high bends rate using the OSHA table both in Seattle and California which was confirmed by the Milwaukee experience. Because of this problem, we obtained a grant from the National Institute of Occupational Safety and Health to devise new decompression tables for tunnel workers. Using Peter Edel's computer memory bank which contained data on 15 years of successful and unsuccessful dives in the Gulf of Mexico and elsewhere, the computer was directed to construct a line between safe and unsafe decompressions. The final result was that the Milwaukee tables which were prohibitively long when air was breathed for decompression (Kindwall *et al.*, 1983). Thus, truly "safe" tables seemed incompatible with the use of compressed air in underground construction or caisson work. However, when an oxygen decompression variant of the table was developed and tested, the decompression times compared favorably with the present OSHA schedules.

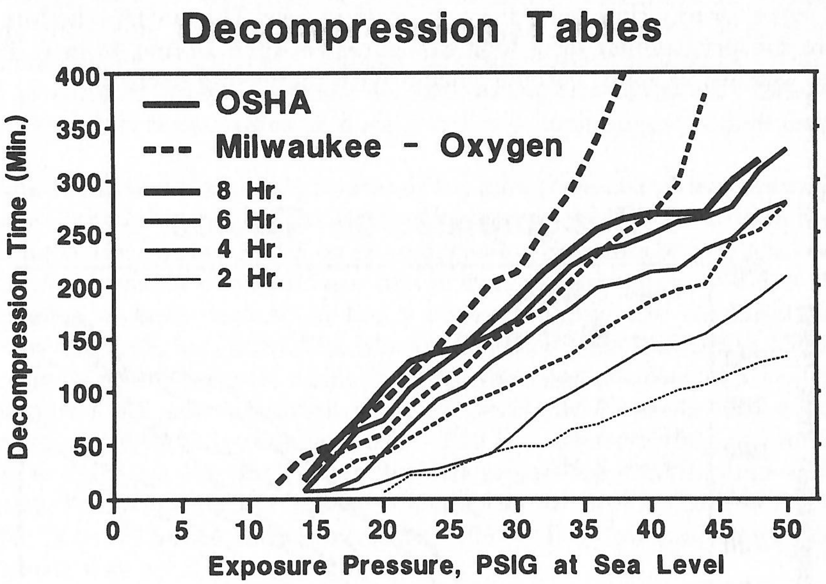

Fig. 3. Milwaukee and OSHA tables compared.

The reason Edel's decompressions were so long was that he included commercial diving data, altitude work and data from his own experiments. Previously, most investigators had relied almost exclusively on naval data for extrapolating to tunnel exposures. However, navies have little or no experience in the extremely long exposures used by tunnel workers, the stressfulness of which is compounded by an unbroken string of daily decompressions which may go on for months or years. Decompressions from 7 and 8 hr exposures are getting close to limits we would consider for saturation. The new oxygen tables were tested in increments of 0.14 kg/cm^2 (2 psig) from 14 to 46 psig (.95 bar to 3.13 bar). Spot checking of these tables using the longest shifts which could be fitted into an 8 hr working day failed to produce any decompression sickness or aseptic necrosis in our test subjects. These tests, of course, could not predict an incidence of decompression sickness but could only rule out a catastrophic error.

Tunnelling has taught us that daily decompression from extreme exposures even at modest depth require inordinate lengths of time if air is breathed during decompression. However, I am beginning to doubt that even long air decompression can accomplish this reliably. In Milwaukee

we have had bends symptoms following 7 hr exposure to 15.5 psig followed by 54 min decompression. Behnke has remarked that the same incidence of decompression sickness may be seen after the same exposure with widely divergent air decompression times (Behnke, 1969). For all the above reasons I believe that air decompression has now shown its limits.

III. COMPARISON OF TABLES

Fig. 4 shows the OSHA table compared to the U.S. Navy decompression table. Note that at pressures from 15 to 25 psig, the OSHA table is equal to or slightly more conservative than the Navy table but at higher pressures for longer times, the Navy table is much more conservative. These 6 and 8 hr exposures on the Navy table, however, were taken from the exceptional exposure air tables which have shown a bends incidence between 17-33% on test. Therefore, one would predict that the OSHA tables would be inadequate for the longer time periods. The irregularities seen in the OSHA table curves are due to the fact that these tables were put in final form by placing a ruler across a nomogram. A very slight movement of the ruler can produce the abberrancies noted.

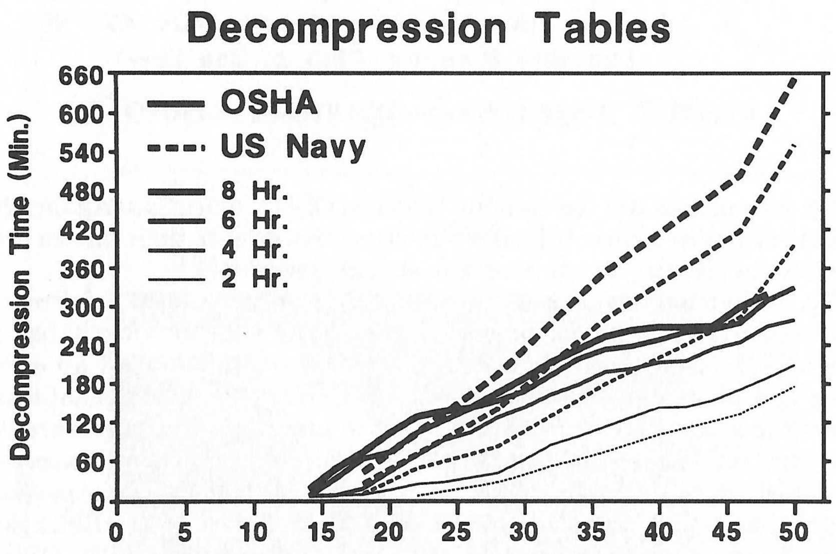

Fig. 4. OSHA table and U.S. Navy schedules compared.

Fig. 5 compares the French air table to the OSHA table. Note that it is much more limited and that work at above approximately one bar is not permitted for more than a duration of 4 hr. The French tables appear to be inadequate by OSHA or Navy standards but obviate many problems by not permitting long duration work at high pressure.

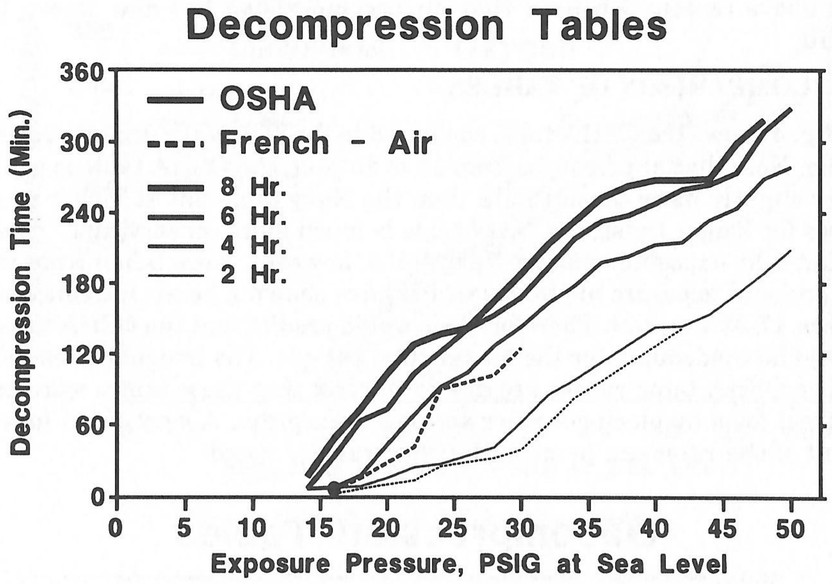

Fig. 5. French air table and OSHA table compared.

Fig. 6 compares the German air tables to OSHA schedules. Again, the OSHA schedules appear to be more conservative despite their known predilection to produce aseptic necrosis at high pressure.

Fig. 7 compares the exposure limits of the various tables. The French are most conservative, cutting back their time sharply after 1 bar is reached. The Germans are next in line. Blackpool tables limit all exposures to a maximum of 8 hr at 3.4 bar but note that the diagonal lines depict the area where decompression is the same at a given pressure for any work period between 4 and 8 hr. The U.S. Navy exceptional exposure air tables go to 12 hr but have been arbitrarily cut off for exposures deeper than would be of interest in tunnel work. They, like the Blackpool tables, increase decompression in 4 hr increments of exposure. The OSHA tables are shown to extend infinitely as a schedule is given for "greater than 8 hr" for all of the working pressures up to 46 psig (3.13 bar).

Figs. 8, 9 and 10 show a comparison of the decompression times for 4, 6 and 8 hr work at 1.5, 2.0 and 3.0 bar. The "X" above the vertical bar

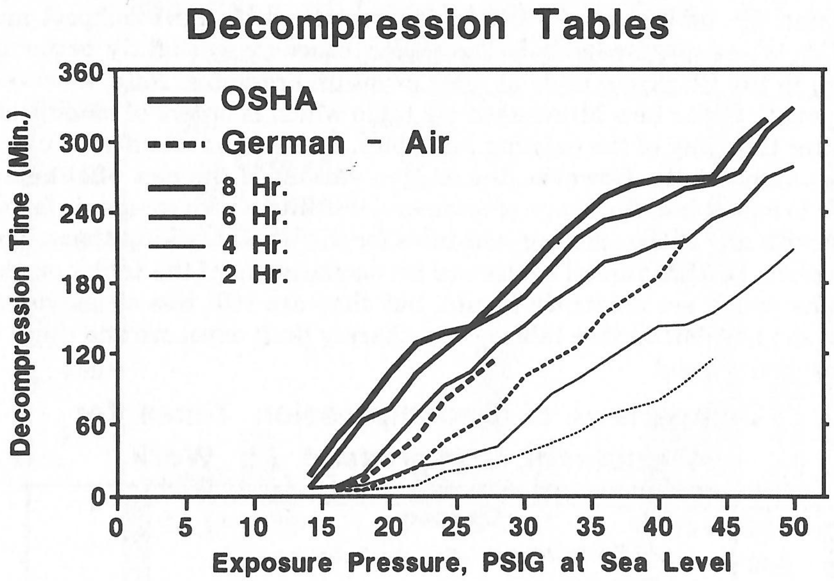

Fig. 6. German air table and OSHA table compared.

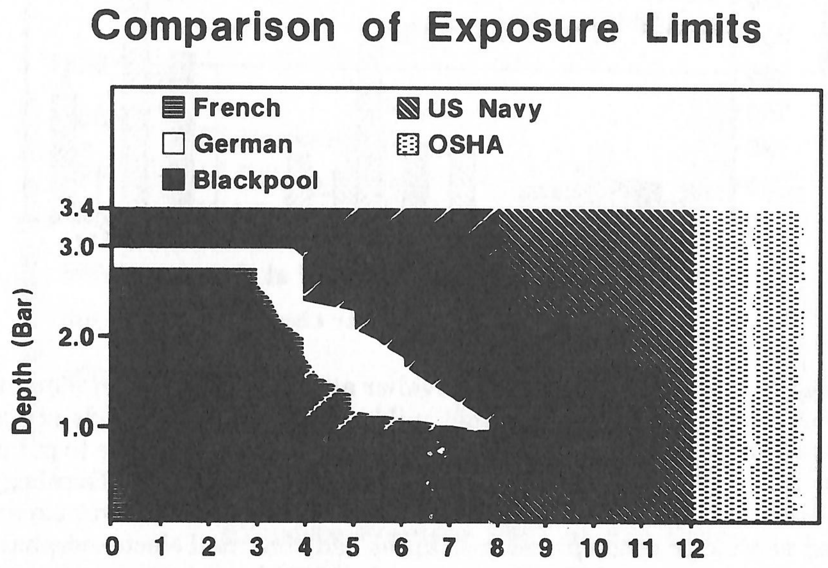

Fig. 7. Exposure limits of various tables compared.

indicates an oxygen variant of the table. At the pressures noted, the German air tables are the least conservative with the Blackpool and OSHA tables not far behind. The OSHA schedule is slightly better or equal to the Blackpool table at most exposure pressures. Note, however, the length of the new Milwaukee air table which is orders of magnitude greater than any of the existing air tables. This is what renders it unusable commercially. However, the oxygen variant of the new Milwaukee table brings it into the range of commercial utility which compares favorably with any of the existing schedules for the usual working times. The Canadian DCIEM tunnel tables are better than any of the tables on the graphs which are currently in use, but they are still less conservative than the new Milwaukee tables, they sharply limit exposure and there is no oxygen variant.

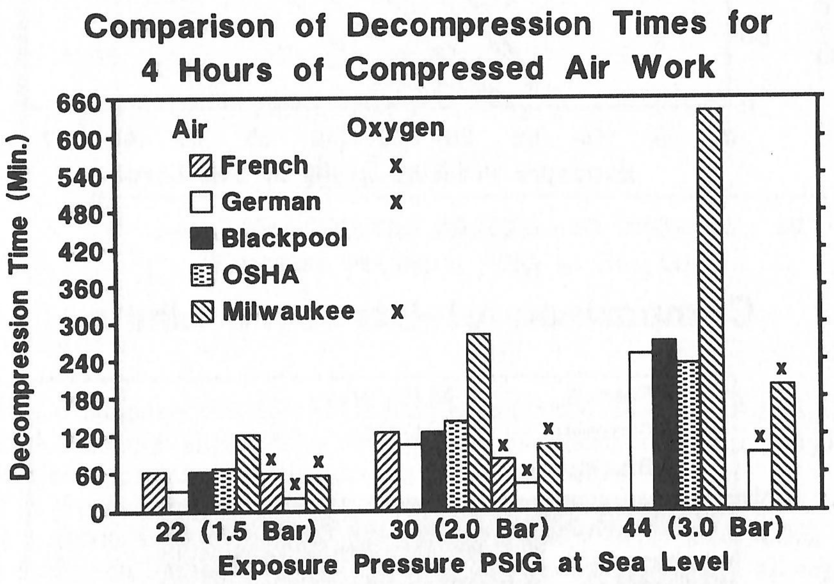

Fig. 8. Comparison of tables for 4 hours work.

Traditionally, there has been a cavalier attitude in the tunnel industry and also among physiologists that mild musculo-skeletal bends are an annoyance, but really nothing more, and that we shall just have to put up with them. This attitude is no longer tenable. In 1965, Rozsahegyi reported that 42% of Hungarian tunnel workers who had never experienced neurologic decompression sickness had abnormal electoencephalograms (Rozsahegyi, 1967). Gorman *et al.* (1986) have demonstrated abnormal EEG's, abnormal psychometric testing and abnormal CAT scans

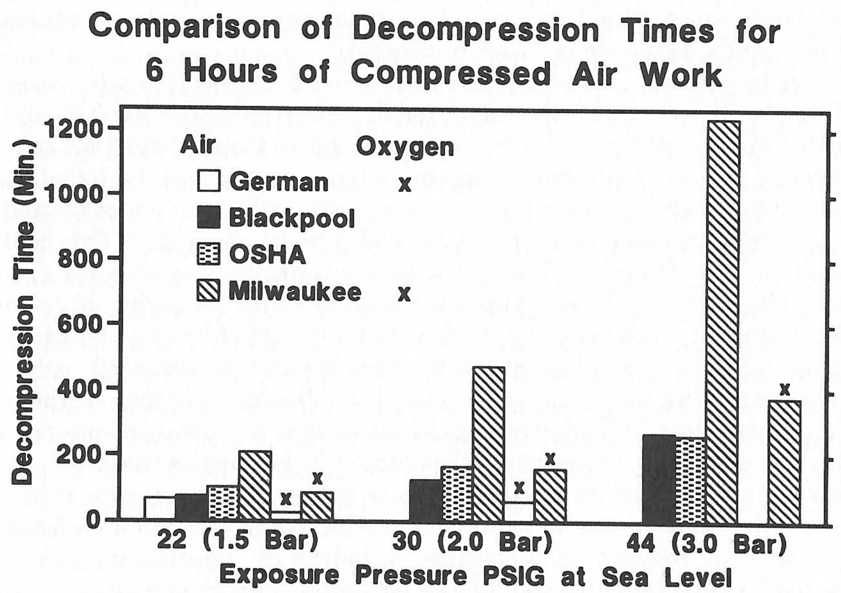

Fig. 9. Comparison of tables for 6 hours work.

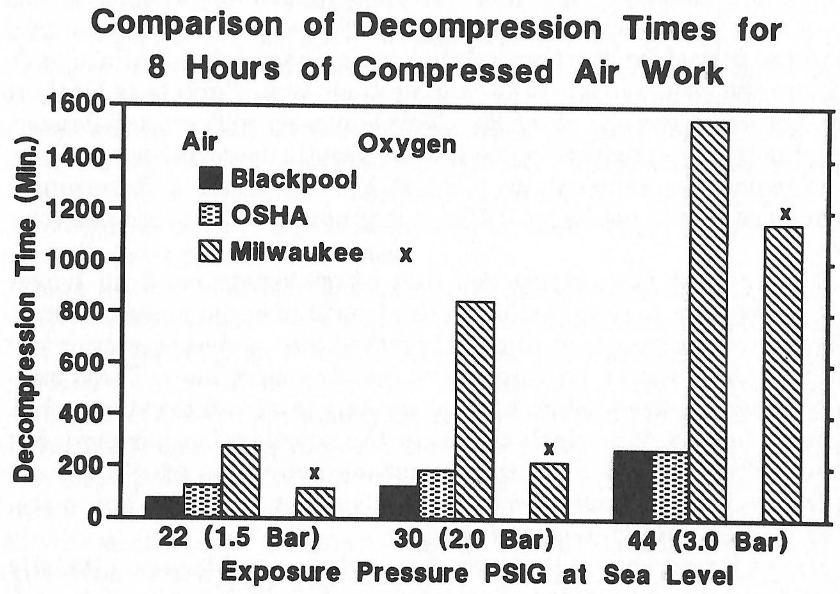

Fig. 10. Comparison of tables for 8 hours work.

showing brain atrophy in divers who have been treated for pain only bends. There must be no letup in our effort to improve caisson schedules until the bends incidence is *truly* minimized.

Tunnel tables are necessarily different than dive tables in what they provide. Ideal tables should be computed for all pressures above 0.90 Kg/cm^2 in 0.1 Kg/cm^2 or 1 pound increments. Exposure times should not only be listed in regular half-hourly increments, but should also be listed as the maximum working time at any given pressure which, when combined with the decompression time, produces and 8 hr working day. This will make them "user friendly". The Germans are the only ones who have attempted this thus far. I favor this approach, even for countries where a greater than 8 hr workday is acceptable, as I feel that at least a 16 hr surface interval should be afforded the workers before the next shift. Additionally, exposures of exactly 4 hr and 6 hr should be listed, as these divide evenly into a 24 hr day and make either 4 or 6 work shifts possible per day. On some jobs, the working face cannot be left unguarded between shifts, so one shift must immediately relieve the other. On this type of job, the only other alternative is to erect breasting boards between shifts, a costly and time consuming procedure. A listing of "no-decompression" exposures for each pressure should also be supplied for brief visits of one-time visitors such as company officials and the physician. Finally, repetitive exposure schedules must be provided to accommodate non-shift workers such as inspectors, electricians, engineers and others who need to be in the tunnel for short periods more than once a day. Failure to do this forces the people involved to "add up their times" and take all their decompression at the end of the day. This is non-physiologic and dangerous, and may have produced some the the aseptic necrosis seen in Hong Kong (Personal Communications, Walder, 1987; Yau, 1987). These multiple schedules should not be too difficult to produce with the aid of a computer.

It is clear from past experience that physiologists must no longer permit themselves to compromise on the length of decompression times, the decompression profile or the gas breathed during decompression out of deference to tradition or contractors' and unions' wishes. These compromises have always produced tables ranging from bad to catastrophic. Economics *do* play the principal role in the construction business, but those who derive tables must supply useable schedules which will not cause injury. Our job is not to compromise based on tradition, but to protect the worker through new technology.

Of utmost importance is that *any* new table enacted into an officially enforced regulation be labeled as an *interim schedule*. A method for quick modification of the new table as experience dictates must also be included in the regulation. This will avoid the present dismal situation where a given table is known to be bad but it must be grudgingly enforced because there is no mechanism to abolish it. In Russia all tables are brought up for automatic change every five years should any need have arisen.

Oxygen decompression which was first used in tunnelling on a regular basis by the Germans in 1972 and then adopted by the French in 1974 seems to be the only viable daily decompression technique which is acceptable for tunnelling. Based on comparisons in our computer data bank, the French and German tables seem to be too short. Indeed the Germans report that they plan on revising them although they have reported a "remarkable drop in decompression sickness despite longer shifts" (Personal Communication, Altner, 1986). The French have reported no aseptic necrosis since the adoption of their tables in 1974, but as yet these new oxygen tables remain to be tested on a large project (Personal Communication, LePechon, 1987). Brazil used oxygen decompression successfully in 1975 in the construction of the Sao Paulo subway with a nearly 80% drop in decompression sickness (Personal Communication, Ribeiro, 1985).

Because of a tunnel fire which occurred during early experimentation with oxygen decompression in Japan in the early 1960's there has been much resistance on the part of the British and American regulating bodies to adopt oxygen decompression. This is despite the fact that some 14,000 experimental oxygen decompressions were carried out without mishap in 1938 and 1939 in the City of New York during the construction of the Queens Midtown tunnel (Jones *et al.*, 1940). The oxygen delivery system was poor on that project, providing the workers with too much breathing resistance. Nevertheless, there were no serious cases of decompression sickness in those workers who breathed oxygen. The main advantages of oxygen are vast savings in time, which of course makes economic sense for the contractors.

There are other advantages of oxygen decompression which are frequently not considered. End, in 1939, described a marked reduction in blood sludging in bent animals concommitant with simply raising the arterial Po_2 (End, 1939). Recently Mathieu *et al.* (1984) have reported that red blood cell filterability is doubled after 15 hyperbaric oxygen treatments. The need to improve the filterability of the blood during and after decompression is underscored by the work of Pimlott, Ormsby and Cross who found that white cells show an 81% decrease in deformability and filterability after exposure to air at 1.5 bar for 4 hr (Pimlott *et al.*, 1987). The toxicity of oxygen is well understood and its early signs, should they appear in tunnel workers, are easily reversible. This is not true for brain damage and bone disease.

The regulatory bodies in Great Britain are nevertheless adamant in refusing to accept any change in the present tunnelling decompression schedules until it can be assured that "no new risk is added." The United States is slightly more advanced in that the Office of Variance Determination of the Occupational Safety and Health Administration has now indicated that "oxygen decompression may be feasible" and they will permit contractors to apply to use this method under an "interim order" (Personal Communication, Concannon, 1987). Based on the known record of the present OSHA tables to produce bends and bone necrosis, we petitioned the Secretary of Labor to rescind these tables immediately as an imminent hazard, but we were told that it may be up to nine years from the time the first report of aseptic necrosis appeared in the open literature until these tables are rescinded. Meanwhile, U.S. contractors may be permitted to work under an interim order when the Office of Variance Determination is able to supply its "standard" for the workplace.

On August 2, 1988, Dr. Ralph Yodaiken, Director of the Office of Occupational Medicine of OSHA, circulated a memorandum to his staff regarding the present U.S. tunnel decompression tables. The memorandum indicated government acceptance of the inadequacy of the present tables stating, "(they). . . are flawed by modern standards" and that "The OSHA tables have failed any reasonable test of adequate performance over the past 16 years." He went on to say, "there is no dispute within the scientific community that the (Autodec III) oxygen tables would be a great improvement." He also stated that, "The Undersea and Hyperbaric Medical Society in Bethesda can be instrumental in developing training requirements. With these and other requirements cited by Dr. Kindwall, oxygen decompression can be very safe as proven by the German, French and Brazilian experience. In summary, oxygen decompression is long overdue in caisson work."

In line with this recommendation, I am developing a training package and intend to submit it to the Hyperbaric Chamber Safety Committee of the UHMS for review and approval before submission to OSHA.

Nevertheless, I am told by an OSHA staff member that even under the most *optimal* circumstances, it will be at least two years before the present tables are rescinded.

IV. CLINICAL EVALUATION

We recently have gathered data, however, which may conceivably speed this process. We used Magnetic Resonance Imaging (MRI) to look for brain damage in compressed air workers. At this time I would like to acknowledge the work of co-investigators Dr. David Czarnecki and Dr. George Fuerdi of the Department of Radiology, Randall Daut, Ph.D.,

psychologist, St. Luke's Medical Center and also Paul Grebe, a fourth year medical student without whose assistance this work could not have been completed. As of two weeks ago, we finished MRI studies of the brain in 28 tunnel workers, 20 of whom had worked in compressed air and 8 who had worked in tunnels but had never been exposed to compressed air. The MRI's were carried out using a new Phillips Gyroscan® Model S-15, a 1.5 Tesla machine. It was capable of 10 milli-Tesla gradients and had 5.5 level software.

With the exception of two tunnel inspectors, one in the compressed air group and one in the control group, all were from the Laborers Union. The mean age difference between the two groups was only 1.9 years, the compressed air group averaging 54.5 years (range 34-63) and the control group being 52.6 years (range 38-65). The mean education of both groups was 11 years. Four men in the compressed air group were illiterate and one was illiterate in the control group. In those individuals, the Shipley test of verbal IQ could not be utilized. In 12 of the 20 compressed air workers, excessive alcohol consumption was noted in the history. Of the 8 control subjects, 5 out of the 8 had a history of excessive alcohol consumption. Three of the 8 controls had a history of head trauma with unconsciousness versus 9 of the 20 in the compressed air group so those parameters were similar. To our knowledge, there were no insulin dependent diabetics in either group. We asked about current medications, but not specifically about insulin.

The Shipley verbal IQ scores were 30.6 in the compressed air group and 30.1 in the control group. Among literate subjects, the Shipley score is thought to correlate best with innate intelligence and is supposed to suffer least in dementia and later impairment from any cause. Our subject groups were incredibly well-matched with regard to innate intellectual ability. Subjects were also given neurophysical evaluation with tests of hand to eye coordination in both the left and right hand (pegboard), a digit symbol test, trailmaking of two kinds, going from point to point with a pencil and a letter cancellation test. Trailmaking and letter cancellation were scored both for time and number of errors. In all there were 10 separate scores of mental performance.

The MRI scans were analyzed for unidentified bright objects (UBO's), ventricular size and an estimate of cortical atrophy. Only the number of UBO's and ventricular size could be quantified precisely. The assessment of cortical atrophy remained the radiologist's impression. Two independent radiologists reviewed the MRI's blinded as to whether they were compressed air workers or controls. It was the radiologist's impression that cortical atrophy was greater in the compressed air group, but this remained only an impression. Four the the compressed air group had enlarged ventricles versus none for the controls but this was not statistically significant. However, the compressed air group averaged 3.8 UBO's (range 0 to 17.5) versus 0.4 for the control group (range 0 to 1.5). This was significant with a p value of 0.02. Nine of the 20 compressed air workers had UBO's whereas three of the 8 controls had UBO's. Half point units on the UBO scores indicate an average between the two radiologists' independent recognition of UBO's.

Unidentified bright objects are associated firstly with lacunar infarcts secondary to vascular disease, second most commonly with demyelinating disease, third most commonly with gliosis and as a fourth category they sometimes appear without apparent lesions which can be confirmed at autopsy. None of our subjects was suffering from known demyelinating disease. The lesions in multiple sclerosis and other demyelinating diseases tend to be tightly periventricular. Most of our lesions fell into the general periventricular and central white mass areas.

Of the 10 psychometric tests given, the compressed air group scored better on only one (the time taken to complete Trails B) but they made twice as many errors. On one test there was no difference (neither group made any errors on the digit symbol test). However, the compressed air group scored slightly lower than the control group with regard to all of the remaining 8 scores. Although no single test showed a significant difference between the two groups, the difference when all the scores were totaled, showing the 8 out of 10 skewing, was significant at the 0.05 level. This might be expected in diffuse disease.

We tried to correlate an index of previous exposure to compressed air [months of work, times the maximum pressures and an arbitrary aseptic necrosis score (13 of our 20 compressed air workers showed some manifestation of bone disease)], but these could not be significantly related to the presence or absence of UBO's. There were trends, but they did not reach statistical significance, perhaps due to the crudeness of the exposure index and the small sample size.

We were limited by lack of funds in doing great numbers of MRI's and this is admittedly a small sample. However, I think preliminary results warrant further investigation.

On large jobs at high pressure, saturation exposures may be indicated. Here the workers would remain at pressure for a week or two at a time in a pressurized habitat which has some of the amenities of a small submarine. They then would go to work via personnel transfer capsule (PTC) or connecting lock to the heading. The advantage here is that daily 8 hr shifts are possible with no decompression required, and workers are exposed to decompression trauma only once every week or two weeks. Saturation for compressed air workers was originally suggested by Behnke in 1969. It is only now than an economic demand for tunnel saturation is materializing.

V. SUMMARY

In summary, modern caisson and tunnel construction is a high technology industry. Rapid advances have been made in automated tunnelling machinery, but where personnel must be exposed to these pressures, government regulations have failed to keep pace with requirements. Modern advances in decompression physiology have made possible oxygen decompression which is not only more economical but vastly safer than traditional air decompression. The diving industry has led the way in this respect. However, even though these techniques are now available to the tunnelling industry, bureaucratic inertia must first be dealt with so that further damage to the brains and bodies of tunnel workers can be avoided.

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