DAN

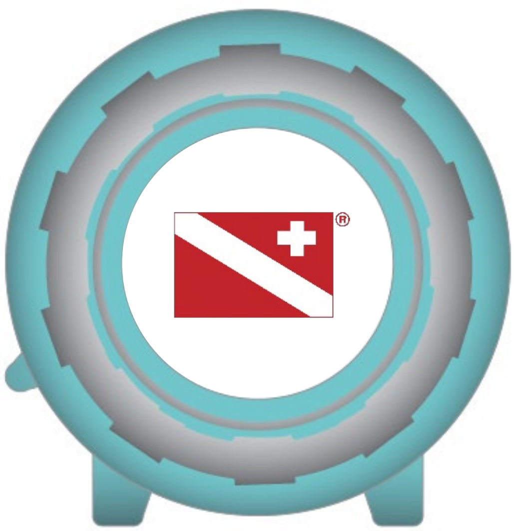
RECOMPRESSION CHAMBER NETWORK

October 1

OPERATOR 2023

A customized manual for the training of hyperbaric chamber operators for recompression treatments.

Chamber Course



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Introduction

This common module for the hyperbaric chamber operator and hyperbaric attendant training programs, has been designed and created based on the requirements to provide sufficient theoretical and practical knowledge to be able to safely operate a recompression chamber used to treat divers suffering from decompression illnesses.

When combined with the chamber attendant module, and on completion of the hands-on practical training, the complete course meets the requirements for certification by the Divers Alert Network (DAN).

The complete course is intended to meet requirements of the National Board of Diving and Hyperbaric Medical Technology for (NBDHMT), based in the USA, for continuing education credits.

The content of this manual specifically applies to the following personnel:

- A **chamber attendant** who is responsible for care of a patient inside a multiplace chamber, within the limits of their medical qualifications and under the supervision of a licensed physician.
- A **chamber operator** who has the sole responsibility for the safe operation of the hyperbaric system, according to the standard operating procedures.
- An **operator assistant** who is able to operate the chamber, but serves to assist in chamber operators, perform emergency functions, call for help, and document treatments.
- A **technician** who is responsible for the maintenance and repair of equipment.

As an entry requirement, the chamber operator candidate must meet the following minimum requirements:

- Current Basic Life Support Certification, or higher.
- Be declared medically fit by a licensed physician to work under hyperbaric conditions.

The materials presented in this manual are relatively elementary, and do not represent a full technical manual. This is regarded as sufficient for chamber operators and attendants to provide recompression treatments safely and effectively.

We trust that you will find this learning opportunity valuable and that you will gain the necessary confidence in providing treatments to patients and non-divers alike.

All pictures or products used or stated in this manual have mostly been taken at recompression facilities, are illustrative and represent what is typically in use, but do not serve to endorse any particular manufacturer.

Further suggested reading for these training programs includes:

- European Code of Good Practice for Hyperbaric Oxygen Therapy (Vol 5, Supplement 1, December 2004; ISSN 1605-9204)
- Handbook on Hyperbaric Medicine (D Mathieu, ISBN 1-4020-4376-7
- EBAss resource manual, which can be found on www.ebass.org
- The DAN Risk Assessment Guide for Recompression Chambers (F Burman, ISBN: 978-1-4507-8885-4) available from Divers Alert Network.

General - Recompression Chambers

There are many different types of hyperbaric chambers that may be suitable for the treatment of an injured diver. Below is a list of some of these, with an explanation as to the suitability for scuba diver recompression.

Let us start with basic definitions of chambers in terms of their use.

A **decompression chamber** is used to provide surface decompression to a diver that either elects to complete their decompression obligation on the surface, or where a diver is brought to the surface from a deep dive in a diving bell that can mate with the decompression chamber. This is not a medical application.

A **recompression chamber** is used to recompress a diver back to depth where medical treatment for decompression illness can commence.

A **saturation diving chamber** is intended for long-term and deeper diving where the divers remain under pressure for long periods of time, are fully saturated with inert gas, and then require a decompression chamber to be brought back to the surface.

A **transport chamber or hyperbaric stretcher** is used where the dive site is remotely located, and to allow the diver to be put under pressure as soon as possible, able to breath oxygen, and then transported under pressure to a suitable recompression facility.

Single-Lock Chambers

In the diving industry, single lock chambers are generally used for transporting an injured diver while under pressure. These are correctly referred to as hyperbaric stretchers. While these chambers are generally small enough for onsite handling and transportation, the major drawback is that no-one can locked into the chamber to attend to the patient. These find use in military applications, where provision is made to lock the chamber onto a larger chamber, where the diver can be attended to by medical or support staff.

Single-lock chambers can also be designed to have more than one person inside the chamber at a time. This allows an attendant to provide basic monitoring of and assistance to the injured diver, including basic airway management.

One-person compartment, correctly referred to as a hyperbaric stretcher. These are intended to fit inside a larger chamber for the patient to be removed under pressure and provide for hands-on assistance.

While any of these chambers might be suitable for use where there is no alternative, they are not recommended for use for recompression therapy.

One-patient, single-lock chambers.

Note the male bayonet flange on the chamber that allows coupling under pressure to a larger chamber fitted with a female bayonet flange.

Single lock medical chambers

Medical single-lock chambers can provide for one person (monoplace chamber), or several people (single-lock multiple occupancy chambers.) These are generally used for more routine medical treatments rather than seriously ill patients.

Twin (Dual)-Lock Chambers

Twin-lock DDC

Twin-lock recompression & medical chamber

Two-compartment chambers are the mainstay of commercial diving facilities, and are commonly referred to as Deck Decompression Chambers (DDCs). These allow for occupants to be transferred into and out of the chamber while the inner lock remains under pressure - referred to as transfer-under-pressure.

These are also typically used for recompression, either by the dive operator, or to recompress other injured divers such as recreational or technical divers. The configuration allows for a diving doctor, medical person or simply an attendant to be locked in and out as may be required. They may be as small as a 2-person chamber (2 occupants in the treatment compartment) or 16 occupants or even more.

Basic Criteria for Chambers

It is evident that some of the above facilities are not appropriate for the treatment of severe diving injuries.
The most suitable type of chamber for use in recompression therapy of injured divers would include the following features:

- Pressure vessel for human occupancy (PVHO): Implies that the pressure vessel is specifically constructed to house human occupants, which differentiates it from pressure vessels used for other applications such as storage of gases (an air receiver), etc.
- Dimensions sufficient to accommodate at least one diver lying in a horizontal position: this means that the chamber should be long enough to allow the tallest diver to be able to lie down.

- Able to accommodate at least one other person: This person, generally referred to as the Chamber Attendant (or Attendant), should be able to remain in the chamber while the injured diver lies down, in order to be able to attend to the injured diver. It is expected that the attendant should be reasonably comfortable, especially when considering that most standard treatments last in excess of four to five hours.
- Allows for the egress and ingress of personnel while the occupants are under pressure: This implies that a twin-lock chamber is available. Single-lock chambers are not ideal to provide treatment for injured divers who are severely compromised or where you could expect complications.

There is one caveat: an attending, registered physician has the final say in what chamber may be used. It is important to involve the local physician in any decision to procure or use any form of hyperbaric chamber.

Chamber Systems and their Components

An integral part of the chamber operator's competencies is to know the purpose and use of the main systems of the chamber.

- Chamber locks
- Pressurization
- Depth control
- Exhaust
- Treatment gas supply
- Treatment gas exhaust
- Electrical supply
- Lighting
- Fire-suppression
- Communications systems
- Environmental monitoring/control
- Visual monitoring (CCTV)
- Emergency equipment

Let us look at each of these system functions individually, with specific attention to what the operator should be aware of

Chamber Locks (Compartments)

Recompression chambers are usually constructed with the following air locks:

a. Entry lock

   In most chambers, access to the main (treatment lock) is done through the entry lock, also referred to as the transfer lock.

   This allows for transfer under pressure should an occupant need to leave the chamber, or someone needing to enter the main lock, with the main lock remaining under pressure,

   The entry lock is usually left open during treatments to allow emergency access into the chamber.

   Some chambers are fitted with doors on either end, allowing patients to enter without having to climb or pass through the entry lock.

b. Main lock

   The main lock, also referred to the treatment lock, is the location where recompression treatments are provided. They are required to have sufficient space for at least one patient and one attendant to remain inside the chamber for the full duration of the treatment, as well as admitting a physician to enter and provide necessary emergency assistance.

   Main locks may be fitted with seats, bunks or stretchers, or a combination thereof, with some of these being able to be removed as required.

   A chamber is generally classified by occupancy in the main lock: a 2 person chamber allows for one attendant and one patient; a 6 man chamber typically 5 patients and one attendant.

c. Medical lock

   A smaller type of transfer-under-pressure is ideally fitted to a recompression chamber. It may also be referred to as a service lock, and larger version referred to as an equipment lock.

   This allows for the rapid transfer of medicines, food, waste and other suppliers into and out of the main lock.

Pressurization System

In order to dive or pressurize a chamber, to provide the appropriate ambient pressure for the treatment table selected, and to ventilate chamber when at depth, a compressed air system is required.

This is usually made up of a compressor, or compressors, and air storage facility and filtration system, collectively referred to as the compressed air production system, and then pressure control system, chamber inlet valves and a silencer inside the chamber, referred to as a pressurization system.

The key functions and components of each of these is described below:

a. Compressors

   Two types of compressors may be used to dive a chamber, viz. low-pressure and high-pressure systems.

   Low pressure (LP) compressors are generally the less expensive option, have a higher air delivery per power rating, require less electricity to perform a treatment, and have lower maintenance costs. However, as these produce air as needed, treatments cannot be provided, or in some cases, continued, should there be a power outage.

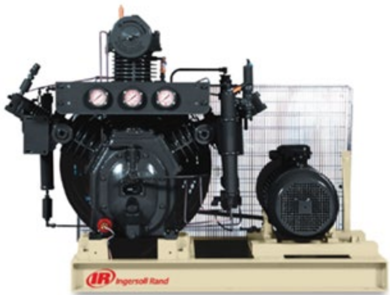
2-stage LP air compressor

   Filtration of low-pressure air to remove moisture can be a challenge, requiring specific moisture removal equipment.

   These compressors usually provide compressed air at between 100 – 125 psi (7.5 – 15 bar) with a delivery capacity of 7 – 100 cfm (200 – 3,000 LPM).

   High-pressure (HP) compressors are conversely more expensive, have a lower air delivery per power rating, require more electricity to operate, and have higher maintenance costs. However, when combined with a typical storage bank, there should be sufficient air to provide a full treatment in the event of a power outage.

   These compressors are typically rated as 2,000 – 5,000 psi (140 – 345 bar), with a delivery capacity of 5 – 30cfm (140 – 850 LPM).



3-stage HP air compressor

   Moisture removal is general easier due to the high pressures generated and the inability of the air to contain moisture.

b. Air storage system

   Based on the type of compressors used, these systems are either lower pressure, high physical volume pressure vessels, or high pressure, low physical volume cylinders.

It is important to match the number and volume of storage vessels to ensure that the chamber can be pressurized at an acceptable rate, as well as storing sufficient air to ensure optimum running of the compressors.

HP air receivers

HP air cylinders

Low pressure volume tanks are usually sized to provide a suitable buffer and sufficient volume to perform a rapid pressurization. Unless a large number of these are used, they are not usually able to start and complete a treatment table in the event of a power outage.

High pressure cylinders are usually provided with sufficient capacity to complete an entire treatment in the event of a power outage.

The desired capacity of the stored gases, for both LP and HP systems is determined knowing the chamber lock volumes, using Boyle's law ($p_1V_1 = p_2V_2$) and providing for one pressurization to maximum treatment depth, 2 transfers under pressure for the entry lock, and sufficient air to ventilate the chamber during treatment.

Ventilation rate is usually computed, using the US Navy Diving Manual, as number of occupants breathing 1 acfm (28 ALPM) at depth for the full duration of a treatment. However, as patients, and at prescribed times the attendant, can be on oxygen, this rate can be reduced to provide ventilation during air-breaks, and 1 scfm (1 ALPM) for the attendant only. The size of the chamber, elevated carbon dioxide (CO_2) or oxygen (O_2) levels and the comfort levels may dictate increased ventilation rates. Ventilation can be noisy and hence reduced levels may be used.

However, the LP compressor output, or HP bank should be sufficiently sized to maintain maximum ventilation rates.

c. Air filtration system

Breathing air quality according to the presiding requirements of the relevant country is required to be maintained at all times. This is ensured through using appropriate air filters, and maintenance of both the compressor(s) and filers.

Typical filtration systems may use all, or a combination of the following elements, usually assembled in the following order:

i) Water (and oil) separator

This is usually a mechanical device which temporarily slows down the speed of the air and causes sudden changes in direction.

Often used after an interstage or after-stage air cooler, moisture containing water and oil is forced to drop-out of the air flow, accumulates at the bottom of the bowl, and is then vented to atmosphere.

Liquid products released by the separator are environmentally toxic and must be collected and then disposed of responsibly.

Moisture separator

ii) Aftercooler

Air or water coolers are used to reduce the temperature in air after compression stages.

These are usually coiled or finned tubes, with a fan use to flow air over them, or a pump to circulate water over them.

This enhances the effectiveness of the separators to remove moisture from the compressed air.

Well ventilated or even air-conditioned environments further enhance effective functioning of aftercoolers.


Aftercooler

iii) Refrigerant dryers

Compressed air can be further cooled using a regular refrigeration process. Cooling compressed air has a dramatic effect on the ability of the air to hold onto moisture. These devices will usually ensure very dry air being produced for both LP and HP compressor systems.


Refrigerant dryer

iv) Regenerative dryers

Where moisture needs to be controlled at a high level, adsorbing chemicals (desiccant) such as molecular sieve or silica gel are used. The term regenerative implies that the chemical is heated once saturated to drive off moisture, and is then reused. These are not commonly found in basic recompression chamber facilities.


Regenerative dryer

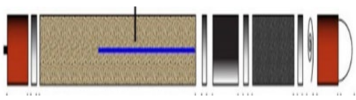
v) Filtration system

A series of filtration processes are used to remove the remaining moisture, oil mist, particulates, odor, and importantly and where considered a risk, any CO.


LP filtration system

For low pressure systems, these are typically a series of moisture coalescing, and oil and odor adsorbents. A CO catalytical converter, usually Hopcalite™, may be installed to reduce CO to CO_2.

High pressure systems generally use chemicals to absorb moisture and oil, scrub out odor, and a layer of Hopcalite™ where deemed needed.


HP filter cartridge

d. Air quality analysis

It is imperative to ensure that compressed air for breathing meets safe limits as described in the relevant standards.

Frequency of testing may be determined by local authorities, but in general, the following recommendations should be considered:

- After installation of the compressed air system
- After any major overhaul of the compressor or replacement of piping and receivers.
- Where any contamination is suspected or detected.
- Prior to changing of filter cartridges or chemicals, to determine whether replacement intervals are appropriate.

- Monthly when operating in known potentially contaminated conditions (such as on a vessel, near power generators, chemical or other processing plants) and where testing indicates high levels of contaminants.
- At least quarterly but not less than biannually.

The table below indicates typical maximum allowable contaminant levels, extrapolated from regularly used standards.

	US CGA Gr E	ISO 12021	Oil-free Air
CO_2	1000 ppm	500 ppm	500 ppm
CO	10 ppm	5 ppm	5 ppm
Oil & particulates	5mg/m^3	0.5 mg/m^3	0.1 mg/m^3
Moisture: HP	35 - 50 ppm	35 - 50 mg/m^3	30 mg/m^3
Odor	None	None	None

Notes to table:

1. Moisture is considered a contaminant where corrosion of receivers and cylinders, blockages of pneumatic control systems, or where freezing of high-pressure regulators are of concern.
2. Moisture in LP pressure air is difficult to control, and generally higher levels are expected. A moisture limit of 160 mg/m^3 for air at 145 psi (10 bar) would be realistic
3. A careful risk assessment is needed to determine if contaminants such as methane, volatile organic compounds or other toxic or debilitating compounds may be present. These need to be monitored and controlled where applicable.

e. Pressure control (regulation)

Pressure reducing regulators are used to provide a constant pressure at the control panel, and ensure controlled pressurization and venting. This is especially important when using high pressure air.

HP air regulator

f. Piping

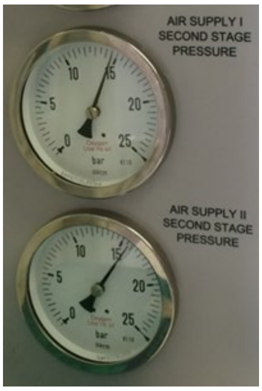
All air supply piping must be copper, a copper alloy, or stainless steel to ensure purity of breathing air. Steel and cast iron are not suitable materials for any gas piping.

Low pressure synthetic hoses may be used where compatible with breathing air.

High pressure hoses (whips) longer than 3 feet (1 meter) that provide air to the regulator are discouraged unless covered and tethered.

Isolating and pressurization valves must be rated for the highest pressure used, are suitable for breathing air, and are located in easily accessible places.

g. Pressure gauges



LP air supply pressure gauges

Pressure indicating gauges must be installed where they are visually accessible to the chamber operator without them needing to leave the control panel.

These gauges can usually only be visually checked for function (zero and operating pressure). Calibration is not possible.

Should the gauge pressure drop significantly during pressurization, these can either be adjusted by another 70 psi (5 bar), or the regulator size needs to be adjusted (increase internal valve size, referred to as the Cv value).

h. Chamber pressurization valve ('air in')

LP pressurization valve

Most recompression chamber facilities utilize quarter-turn (ball) or multi-turn globe valves to dive the chamber to the required treatment depth, or to provide exchange air during ventilation.

Valves need to be clearly labelled to avoid confusion.

Both main and entry locks require individual valves.

i. Internal pressurization shut-off valves

Chambers should be fitted with internal shut-off valves to be used in an emergency where control outside the chamber may be lost.

These valves should be wired open at all times.

j. Silencers


Pressurization silencer

Noise levels during pressurization and venting can exceed comfort levels, and prevent normal conversation inside the chamber locks.

Internal silencers are fitted to control noise levels, although relatively limited in effectiveness. Hearing protection (earmuffs) for chamber occupants is often used.

Chamber Depth Gauges

Chamber depth gauge

Control of chamber depth, and specifically treatment depth, requires accurate and regularly calibrated life-support gauges.

Units of depth are typically indicated in fsw, msw, psi or ATA; Combinations of units are commonly indicated (e.g., fsw and msw for diving recompression chambers.

Gauges should be large enough to allow for clear, accurate readings to be taken.

All locks that are occupied by humans must be fitted with suitable life-support depth gauges.

An internal pressure gauge, usually referred to as a Caisson gauge, should be installed in the ML to provide the attendant with confirmation of chamber pressure.

Gauges need to be calibrated whenever any doubt exists, or at least once a year.

Chamber Exhaust System

All locks are fitted with large bore quarter-turn (ball) valves to ensure that rapid surfacing is possible, especially in the event of an emergency.

Both the main and entry locks are fitted with independently operated exhaust valves.

Controlled exhausting during ventilation requires operators to be well practiced in maintaining the correct valve opening. One has to balance air-in with air-out to retain the chamber depth.

Chambers should be fitted with internal shut-off valves, to be used in an emergency where external control is lost. These valves should be wired open at all times.

Caution is needed to prevent any blockage of chamber exhausts on the inside of the chamber. The flow of chamber air from inside the chamber to the outside is, in essence, a high-vacuum generator – up to twice absolute vacuum pressure. Exhaust outlets must be fitted with anti-suction injury or blockage-prevention devices.

Internal exhaust shut-off valve

Attention needs to be taken to where the chamber exhaust is vented outside the chamber facility. It is normal to dump the treatment gas (usually oxygen) through the same system. Hence the area must be clear of hazards or restrictions, and well signposted with no smoking or open flames signage.

Treatment Gas In

The treatment gas most commonly used in air-diving injuries is oxygen. One can, however, use other breathing gas mixes, such as heliox or nitrox (especially when deeper treatment tables are used).

It is important to note that all of the components should be oxygen-clean when these are used to manage gases with an oxygen percentage that exceeds 25%.

The treatment gas system from the supply to the breathing device into the chamber, as well as the exhaust system, should be followed by the operator to ensure a suitable response in the event of an emergency such as lack of gas or inability to dump the exhaust gas from the chamber.

Typically, the oxygen supply system to a recompression facility that is not installed in a larger healthcare facility, is provided from a high-pressure storage system (bank). Usually, the bank consists of 2 to 3 cylinders connected to a common manifold, with a duplicate system to ensure continuous supply, serving as a secondary system in the event of failure of the primary bank.

HP air bank

Larger facilities (typically those providing regular hyperbaric oxygen therapy) may utilize a cryogenic supply system, with oxygen stored in liquid form. This requires significant usage to ensure feasibility from a cost perspective.

In remote areas where oxygen (high-pressure cylinder or liquid) is not available or cannot be reliably provided, an oxygen gas generator is used. In most cases, generators will only provide an assured purity level of 90 – 93% oxygen, implying that a clinical decision needs to be taken to approve this option.

Cryogenic oxygen storage (LOX)

a. Oxygen storage:

   The oxygen storage should be in an open, well-ventilated space and allow an explosion to blow upwards (and not sideways) if it occurs. It should be clearly marked as hazardous and signs prohibiting smoking should be clearly displayed.

b. Oxygen purity

The oxygen used should be certified medical grade oxygen. Industrial oxygen should not be used in the treatment of a patient.

Certificates of analysis of the oxygen should be reviewed on receipt, and filed at the facility. Oxygen generators should be fitted with audible alarms at the control panel to indicate when oxygen levels fall below the minimum purity allowed.

c. Required volume of oxygen

Where gas is stored in high-pressure cylinders, there should be sufficient oxygen for full duration of the treatment being planned.

Storage volume for both the patient(s) and attendant, determined by the maximum time they are likely to breathe oxygen, must be available at the start of a treatment.

Oxygen bank volume = RMV of occupants at depth when on oxygen x number of occupants x 1.5 x time, expressed in scf or liters The attendant will usually breathe much less than the patient, and this can be allowed for in the computation.

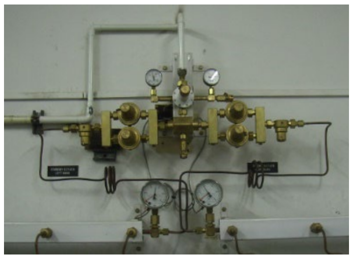
Oxygen generator

RMV (Respiratory Minute Volume) is usually calculated as 0,022m3/minute (22 LPM) when at rest in a chamber.

Where dedicated oxygen generators are used, ensure that the output capacity of the equipment exceeds the maximum flow demand of the recompression facility

d. Connection to the chamber:

The first stage regulator for the oxygen supply should be as close to the high-pressure cylinders as possible (preferably directly on the cylinders when individual cylinders are used) and not further downstream.



HP oxygen regulator system with change-over

Regulators that are further downstream introduce a significantly increased risk to the operation in the event of any rupture!

There should be a mechanism in place to change from one cylinder or one cylinder bank to the other without any significant delay. This could be done during an air-break, or using a change-over maniform system.

e. Oxygen piping:

Oxygen piping should be a suitable metal such as copper, copper alloy, or stainless steel. A small section of flexible piping (sometimes referred to as a whip when a hose, or pigtail when copper), may be used close to the cylinders, but these should be as short as possible (no more than 3 ft or 1 m).

f. Oxygen supply pressure:

The oxygen pressure before the HP regulator should be monitored, especially before a treatment commences. This will indicate the volume of gas is left in the cylinder. Cylinders should be changed over when the pressure drops below 300 psi (around 20 bar).

The regulated (LP) oxygen supply should be clearly indicated on the chamber control panel.

g. Oxygen valves:

Oxygen valves should be located where the gas enters the treatment room (so that the line can be isolated in the event of an emergency), at the control panel, and if the panel is remote from the chamber, at the chamber shell penetration.

Oxygen multi-turn valve

Oxygen valves are usually multi-turn globe valves. Quarter-turn ball valves should not be used, especially where pressures exceed 125 psi (8.6 bar).

An isolating (multi-turn) valve should also be fit inside the chamber, as close to the penetrator as possible.

All oxygen valves must be opened slowly.

h. Inside the chamber - (Built-in Breathing System or BIBS):

The BIBS supply inlet should be clearly marked on the inside of the chamber.

Valves on the inside of the chamber should be closed during the pre-dive checks (the chamber attendant will open these when the injured diver needs to go on oxygen).

The oxygen then usually follows the following pathway inside the chamber:

i) Supply manifold:

The manifold divides the oxygen supply into multiple ports, one per mask, and one spare.

BIBS supply connections

The manifold piping size should be of sufficient size to allow multiple BIBS breathing devices to be used at the same time.

If separate from the shell isolating valve, the BIBS manifold valve should be in the closed position during the pre-dive checks and opened by the chamber attendant when needed.

ii) BIBS delivery devices:

Aviator-type BIBS mask

In most recompression chambers, the patient's breathing device is a face mask fitted with a demand regulator (to allow breathing on demand) and overboard dump regulator.

Some chambers, especially those also used for hyperbaric oxygen therapy, may be fitted with an oxygen hood, supplied with a constant flow control panel.

Treatment hood

These devices are only used where the injured diver is breathing normally.

There should be enough BIBS masks or breathing devices available inside the chamber prior to the start of pressurization. The number is determined as one mask for each occupant (patients plus attendant) as well as one spare. This applies to the main lock and the entry lock.

While breathing devices are primarily intended to provide selected treatment gases to the patient, these are also crucial in the case of a chamber fire, or any contamination, to protect occupants from breathing the contaminated chamber atmosphere.

Treatment Gas Out

It is important that all exhaled oxygen is dumped outside of the chamber, to keep the oxygen concentration in the chamber environment below 23.5%, in order to manage a fire risk.

The following components are typically present in the overboard dump system:

a. Overboard dump control device:

   The pressure differential between the inside and outside of the chamber is in essence an extremely strong vacuum. An exhaled oxygen dump regulator is used to ensure that the occupant is not exposed to this suction force.

   Masks and hoods are connected to a dump manifold, with each hose connection point fitted with an individual isolation valve. These valves must be opened when the breathing device hose is connected. Exhaust ports that are not connected to a hose must be kept closed. These connections are open to ambient pressure outside.

   Oxygen hood systems provide a closed loop where the constant flow into the hood leaves at the same rate, and control is maintained using attendant-controlled flow meters.

b. Back-pressure regulator:

   Chambers that provide for treatment gases used deeper than 66 fsw (20 msw) should be fitted with a back-pressure regulator.

   This regulator prevents a suction injury to the occupants in the event that the “dump” valve fails.

   Some devices e.g., the Scott or Amron Aviator Masks, are only designed to prevent suction injury where the chamber pressure is kept below 66 fsw (20 msw).

BIBS exhaust ports with back-pressure regulator

c. External BIBS exhaust valves:

   The external BIBS dump valve is attached to the through-hull connection and should be opened to ensure the expired gas can be dumped outside the chamber. Some chambers have additional exhaust valves on the control panel.

   The outlet of the dump valve should be either connected to the chamber exhaust system, or to a dedicated exhaust pipe, and should vent to the outside of the facility in a safe area (well-signposted as a fire hazard.

BIBS exhaust shell valve

Additional breathing devices

For a non-breathing injured diver, a hyperbaric ventilator is required. These device require very specific training, and while relatively inexpensive models are available, functionality is often inadequate for critically ill patients.

Hyperbaric ventilator

A bag valve mask (artificial manual breathing unit or Ambu bag) is also used for patients unable to breathe normally. However, this device should only be considered in an emergency – such as where the patient stops breathing on their own. If the chamber is not fitted with a suitable ventilator, the facility should not consider placing such a critically ill patient inside the chamber (unless the attending physician decides to allow it).

Ambubag

AMBU bags typically dump oxygen inside the chamber, requiring constant venting and careful monitoring of the internal oxygen percentage level.

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Electrical Supply

Normal building power (typically 110 – 240 Vac) cannot be used on the inside of the chamber without sophisticated protection devices. Any form of sparking creates a significant fire risk (ignition source).

The following standards should be adhered to inside the chamber (this applies to all "diver" treatment chambers, but does not apply to monoplace, oxygen filled chambers):

- Maximum voltage: 28 V_{DC}
- Maximum Watts: 25W @ 28V_{DC} & 48W @ 12 V_{DC}
- Non-insulated conductors: 0.5 Amps

The chamber operator should follow the supply of electricity from its source to the chamber, to ensure that whenever a problem occurs, the fault can be rapidly addressed. (For example: if the electrical power supply is suddenly interrupted, locating where the problem could be and how it can then be corrected.)

The following is an outline of a typical supply system:

a. Building or facility supply:

   The source of electrical usually comes either from a supply grid, or an electrical generator.

   It is essential a backup supply is available, especially where pressurization depends on constant supply. .

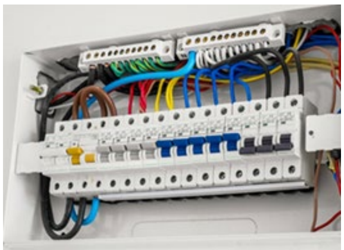
   Generators and battery-supplied systems are most commonly used, with the capacity matched with the minimum requirement to ensure continued and safe treatment.

   Always ensure that you have the contact details of an electrician that can manage problems with the supply source.

b. Distribution board:

   The electrical supply to the chamber facility is usually managed using a distribution board that has a number of isolating switches (circuit breakers), including overload and earth-leakage safety breakers.

   Ensure a clear understanding of which circuits are control by each of the circuit breakers in order to fault find, or isolate a circuit, in the event of an emergency.



Mains distribution board

   Labelling of all distribution board controls that affect the hyperbaric facility is essential – something that must be regularly checked.

c. Electrical wiring:

   All electrical wiring should be well insulated, fire-resistant, robust and protected against damage. Typically, either conduiting, installation behind panels or affixing wiring securely to the chamber structures provides the best form of protection.

d. Voltage/current reduction units (electrical transformers):

   Step-down transformers reducing voltage from the room power outlets to the acceptable supply for use inside the chamber. Internal lighting, scrubbers and internal environmental controls are usually powered by a 12 V_{DC} supply.

   Where a transformer is needed, or needs to be replaced, only use a high quality, insulated and isolated device, fitted with a ground fault indicator (GFI) or earth leakage breaker that supplies ungrounded power to the chamber. This provides protection from sparking inside the chamber where a conductor is loose and touches anything

12 V_{DC} transformer with ground-fault interrupter

   Current limiters/trip switches, or fuses are used to protected against current surges (due to supply irregularities or short-circuits) and are situated close to the chamber control panel. These are essential to ensure that all supplies in and around the chamber are safe.

e. Chamber electrical supply panel:

   Recompression chambers usually have supply and control panels that allow for powering the fitted electrical devices on and off which are typically communications, lighting CCTV, internal environmental conditioning, analyzers, fire alarm and computer systems. Switches are either fitted with disposable fuses or overload-protected brakers. Be sure to know which, as spare fuses are an essential spare part.

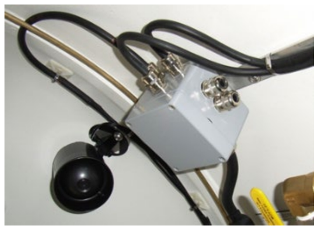
Chamber power panel

f. Connectors, plugs and terminations:

   All connectors must be selected to ensure sufficient current capacity, and where passing through the chamber shell, they must be gas tight.

   Connectors should be locked or secured to prevent inadvertent disconnection – this is especially important inside the chamber.

   Terminations, even where protected using cable clamps or glands, should be carefully monitored for any signs of loose wiring.



Internal connection box

   If there are not enough supply outlets available outside the chamber, ensure that an electrician (or competent person) installs safe multiplug units, fitted with surge and overload protection.

Lighting

Sufficient lighting is needed for all chamber operations. S sunlight or external lighting should not be relied on for illumination inside the chamber.

The following areas should be well lit, and the chamber operator should know where these lights are switched on and off:

a. Chamber complex: The chamber complex and general area should be well lit to prevent injuries to the persons working in the area
b. Chamber operating/control panel: The chamber operator should be able to clearly see all valves used during operation of the chamber. Instruments should be clearly visible, and all gauges should be lit with sufficient light to ensure correct readings.
c. Assistant operator’s desk: This desk should contain all of the chamber operation manuals and the diving and treatment tables used.

The assistant operator is required to document all operations during treatment. Sufficient light must be available to enable the assistant operator to read and write without difficulty.

d. Compressor and gas bank are:

While these do not need to be lit continuously when staff are not present, sufficient light should be available to ensure safe operation(such as during start-up and shutdown, or changing oxygen cylinders). Hand-held flashlights may be used, there may be restrictions where staffing is limited, and the technician requires both hands to perform their tasks.

e. Inside the chamber:


LED inside lamp

The attendant should be able to clearly see everything inside the chamber. It is especially important that the chamber attendant is able to clearly see the injured diver.

Lights may be located inside the chamber, using low-power/low-heat hyperbaric fixtures, or outside the chamber, either through the viewports (as long as low heat fixtures are used) or specially designed chamber lighting (generally referred to as Canty lights).


External light source

Viewport windows must be protected from any source of ultraviolet (UV) lighting, including high-intensity fixtures (mercury or sodium vapor discharge), or direct sunlight. UV shielding is commonly used where this cannot be avoided.

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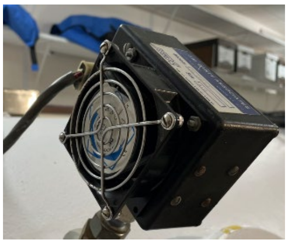

Canty light projector

Viewport windows are also susceptible to infrared sources (specifically lighting, so only power heat lighting should be used anywhere near a window.

LED lighting is considered as low heat.

f. Medical treatment area:

This area generally needs excellent lighting, as the doctor or paramedic may need to do invasive procedures (e.g., insertion of a chest-drain). An individual (movable) light is often used to provide specific illumination of the area the doctor/ medic is working in.

It is perhaps necessary to mention here that special medical lights are sometimes provided inside the chamber. These can be switched on when the doctor or medic is performing an invasive procedure (e.g., putting up a drip) inside the chamber. Once again, care must be taken that such lighting does not generate heat, and is only activated while in use. It is usual to have attendants use suitable flashlights (e.g., dive lights) to achieve high lighting levels.

g. Back-up lighting:

   The chamber operator should have a back-up plan in place in case the primary lighting fails. This may either mean that spare bulbs are immediately available, or that a hand-held flashlight torch or other movable light source is available.

Fire-Suppression

The fire-suppression system is a critical safety feature that should be immediately available and rapidly activated in the event of any fire, or suspected fire.

A clear understanding of the fire suppression system is key in order to ensure that it remains functional at all times.

Two suppressions systems are commonly found in recompression facilities:

- Hand-held water or foam-based extinguishers, or preferably
- Overhead deluge sprinkler systems.

Specific training in the use of either of these is essential.

Pre-dive checks must be carefully performed to ensure that internal extinguishers and/or the overhead deluge system is active and can be used immediately.

a. Hand-held extinguishers, fitted inside all treatment locks

   Hand-held hyperbaric extinguishers are specifically designed to work under external pressure. Operating pressure is typically 50 psi (3.4 bar) above maximum treatment pressure (this implies at least 80 psi or 5.5 bar for a standard oxygen treatment table).

   Portable extinguishers are either water-based or aqueous foam-based. Selection criteria includes sufficient volume, and sufficient pressure to remain effective at maximum treatment depth.

   Hand-held hoses are water-based, and pressurized by a system able to provide water at a minimum of 50 psi (3.4 bar) above maximum chamber operating pressure. The volume of water should be sufficient to operate all hoses, simultaneously, for at least 1 minute. The required flow rate, per hose, should be at least 4 gpm (19 LPM).

Hand-held, portable, water extinguisher

   Simply checking pressure gauges is not deemed sufficient; all hand-held extinguishers must be inspected regularly to ensure that they are filled, charged, and in working condition.

b. Overhead deluge systems, fitted inside all treatment locks.

   Water deluge (sprinkler) systems are the preferred means of provide for fire protection.

   The system should be traced from the supply tank, generally powered by compressed air, to the external and internal activation controls. All supply valves must be in the open position throughout all treatments.

Overhead deluge nozzles

   Supply pressure should be clearly visible on the control panel.

   Automatic detection may be used although not currently mandated.

   Deluge systems are designed to provide sufficient water to deluge all occupants for a period of at least one minute.

Some designs are based on

i) Reducing temperature of a burning occupant sufficiently within 20 seconds, to extinguishing a fire within 40 seconds; while others

ii) Require sufficient water per area of chamber floor (gpm/ft^2 or LPM/m^2), with the floor being no smaller than the area at ¼ diameter, for a period of at least 1 minute. These criteria are used to determine the minimum amount of water needed in the deluge tank.

Air-powered water deluge systems require a pressure of at least 50 psi (3.4 bar) above maximum treatment pressure (typically 80psi or 5.5 bar for oxygen treatment tables).Activation of the fire-suppression system should be possible without delay, either by the operator or the attendant (or any occupant in the event the attendant is incapacitated). A correctly designed system will ensure that water enters the chamber within 3 seconds.

There are five concurrent actions required in the event of a fire, viz.,

i) Change-over oxygen to the BIBS system to breathing air; and

ii) Activate the deluge system, and

iii) Sound the fire alarm – call for assistance, and

iv) Switch off all non-essential electrical systems inside the chamber and

v) Immediately begin surfacing the chamber, as fast as possible.

Deluge systems not fitted with oxygen-to-air change over should be modified as a matter of urgency.

Deluge system should be tested a least twice a year, and attendants well trained so as to know what to expect in the event of deluge.

After activation of the deluge system, water will accumulate under or on the chamber floor, provision needs to be made to effectively drain the chamber after activation.

These systems are generally referred to as the bilge drain, with isolation valves on the inside and outside of the chamber shell.

Hand-held hose systems may also be powered using pressured water tanks or supplies and require the same pressure to ensure adequate function.

Water or sand buckets are deemed inadequate, and CO_2 extinguishers must not be used for fire protection.

Communications System

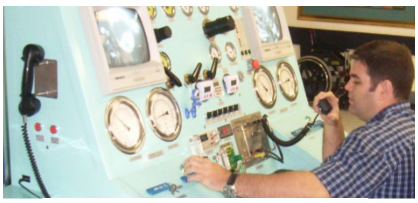
It is important that the chamber operator and attendant can effectively communicate with the occupants inside the chamber, as well as with other persons and facilities outside of the chamber facility, including diving medical specialists who may be far away..

There should be sufficient redundancy in the system to ensure effective communication, including when the primary system fails.

a. Primary communication system:

Continuous audible monitoring of the inside of the chamber is required at all times. The system should be switched on before the treatment starts, and tested to ensure that it is in full working condition.

Volume levels should be set to allow all persons to hear each other clearly without being too loud.



Hyperbaric chamber communications system

The chamber operator should be able to switch this system on and off as required, or change the volume, to reduce the noise levels, e.g., while pressurizing the chamber.

Visible communications with the chamber occupants should be available to allow pressurization – or decompression – in the event of an adverse occurrence in the chamber).

b. Secondary communication system:

Sound-powered phone

The secondary communication system does not usually provide continuous audible monitoring, but it should enable communications through the chamber shell to signal the other side that communication is needed

Sound-powered phone systems and signal hammers are commonly used as secondary communications systems.

c. Discrete communications

Headset & boom mic.

A means of communicating between the operator (or medical officer) and attendant is necessary to allow communication without the injured diver hearing what is being said, to reduce anxiety or fear.

d. External communication systems:

A means of requesting medical assistance, additional support, technical help or medical or other supplies is important to the safe and effective treatment of injured divers.

These may depend on the infrastructure of the region, and typically include:

i) Landline telephone: Ensure that all the relevant telephone numbers are immediate available to the chamber operator or assistant operator, and that these numbers are regularly checked.

ii) Radio or satellite phone -link: -These may be useful in remote areas, or onboard vessels, where no direct telephone connectors or cellular phone coverage is available. Chamber staff need to be versed in the operation of these, including channel selection.

iii) Cellular phone: Cellular phones depend on good signal coverage.

iii) Email: Most recorded communication is now transferred using email. Dedicated addressed to ensure patient confidentiality are required. Email is sometimes the default means of communications where cell phone or other coverage is temporarily unavailable.

iv) Fax: Although outdated, some institutions and medical facilities require prescriptions and payment guarantees to be sent via fax, in order to control any electronic modifications to documents.

v) Assistant operator: In event of a total failure of the facility communications systems, the facility should know where to send the assistant operator to request assistance.

Environmental Control

The environmental control affects both attentiveness of the outside staff, was well as the condition of the occupants.

a. Outside the chamber:

Staff involved in the chamber operation should be sufficiently protected from the from the environment to ensure that they can provide their full attention to the treatment.

Temperature and humid control are important to ensuring sufficient attention and comfort. Room temperatures should not exceed 86°F (30°C).

The facility should be protected against fire from either within the facility, or from outside. Fire extinguishers should be provided in the chamber room as well as in machinery and gas storage locations.

Smoke hoods or air-supplied full-face masks should be installed to provide the chamber operator with sufficient breathing and eye protection to be able to safely evacuation chamber occupants in the event of a fire.

b. Inside the chamber:

The environment inside the chamber changes during compression, decompression as well as during treatments.

The following aspects should be monitored and controlled:

Thermo-hygrometer

i) Temperature:

The temperature inside the chamber should be monitored using a thermometer and kept below 86°F (30°C) as far as possible. Temperatures can be controlled using fresh-air ventilation, as well as internal air conditioning where fitted.

Mercury thermometers are prohibited from use inside recompression chambers.

Thermal comfort is important to ensure improved patient outcomes. Studies have shown that perspiration is less effective when in a chamber. Occupants have thus a higher risk for hyperthermia to develop during long exposures.

ii) Humidity:

Basic humidity meters are usually placed inside the chamber where they are visible through one of the viewport windows. Venting (flushing) the chamber with fresh air will reduce the humidity and is important where occupants complain of discomfort.

The relative humidity should ideally be kept in the 50 – 70% range. This protects the performance of the CO_2 scrubber, where fitted, and comfort of the occupants.

iii) Carbon dioxide:

CO_2 monitor

The CO_2 content should ideally be measured in real-time using an appropriate analyzer, especially in smaller chambers and where air suppliers are limited.

The CO_2 produced by respiration may be removed using a CO_2 scrubber.


CO_2 scrubber

In the event that the scrubber is not capable of removing sufficient CO_2, ventilation should be performed, or failing this, occupants put onto the BIBS should the surface equivalent level of CO_2 exceed 0.5% (5,000 ppm).

CO_2 causes an increase in breath rate as well as vasodilatation associated with CO_2 toxicity. This increases the uptake of inert and other gases, and thus increase the risk for oxygen toxicity, decompression sickness, etc.).

iv) Oxygen:

Oxygen content must be monitored continuously. Even a small leak from the BIBS device (e.g., a diver with a beard that prevents a total seal) will lead to a rapid build-up of oxygen in the chamber.

The normal oxygen content of air is around 21% and the maximum allowed in the chamber to reduce a risk of fire is 23.5%. There does not provide a significant margin for error.

Hyperbaric oxygen monitor

As soon as the O_2 percentage approaches or rises above 23.5%, the chamber should be flushed immediately with fresh air. The attendant should then check for the source of leak(s) inside the chamber, and remedy this.

v) Other Contaminants:

If an abnormal odor is detected, or the occupants report eye or lung irritation, or have symptoms like coughing, headaches, or impaired performance, contamination of the chamber air should be suspected.

CO monitor

Even very low concentrations of contaminants can be deadly at the increased pressure inside the chamber.

Whenever contamination of the air supply is suspected, all the occupants should be placed on a fresh gas supply via the BIBS that is independent of the chamber air supply. the chamber should be vented with fresh gas and the appropriate emergency procedures should be followed.

Visual Monitoring

Monitoring of the inside of a recompression can be done through the viewport windows when sufficient visual access can be maintained, comfortable, from the control panel.

However, it has become standard practice for closed circuit television monitors to be fitted, with modern cameras even being suitable for installation inside the chamber.

Closed circuit TV monitoring

Chamber Emergency/Safety Devices

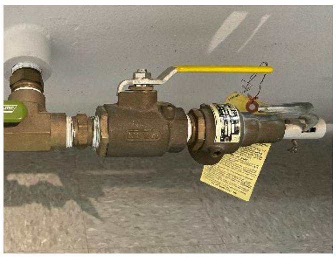
Various technical and operational emergency situations can emerge, requiring the installation of suitable, safety equipment.

Emergency procedures are covered later in this manual, but two items of equipment require mention at this stage.

a. Safety valves

Over-pressure relief valves, also known as safety or pop-off valves, must be fitted to all pressure vessels located in a facility. These include the hyperbaric chamber, air receivers and fire deluge storage tanks.

These devices protect pressure vessels from inadvertent over pressure resulting from a loss of control during pressurization of the vessels.



Chamber relief valve

In the event of a safety valve opening, a deafening noise will result, causing a high level of stress in the location. Staff should be made to experience safety valves opening so as not to panic in the event of any uncontrolled releases.

Recompression chamber safety valves should be fitted with internal and external shell valves, always wired in the open position, to prevent an inadvertent loss of pressure should the safety valve open for any reason at below treatment pressure.

The safety valve inlet will serve as a suction point, and must be protected by a device to prevent materials from blocking the opening.

Internal isolating valve

Safety valves should be tested annually to ensure that they work.

b. Escape valve or system

Internal escape valve

The chamber should be fitted with some form of an escape system ("escape valve") in the event of outside personnel being disabled, or an inability to surface the chamber from the outside.

The chamber attendant must be able to surface the chamber from the inside.

This can be achieved in a variety of ways, and the attendant must identify and be able to use this escape system in the event of an emergency.

i) The most suitable option is a dedicated large-bore valve that can be opened from inside the chamber, and that is not restricted on the outside (the external valve must be sealed in the open position).

ii) A bilge drain system may be used, and once again, the external shell valve must then be sealed in the open position at all times.

iii) The chamber medical (service) lock may also be used, where the controls on the inside of the chamber allow for this.

iv) The BIBS exhaust system can also be used, with the breathing devices detached.

The chamber staff should determine the most suitable means, and perform a check to ensure that the select method is effective and allow the occupants to be able to evacuate the chamber.

Chamber Operating Procedures

Duties and Responsibilities

The following minimum staff compliment should be present during recompression treatments at all times:

- **Attending physician:**

  The attending physician is responsible for the diagnosis, prescription of the treatment table and any subsequent modifications monitoring the condition of the patient and tender, and responding to medical emergencies or changes in condition. The physician should be present at the chamber during initial treatments, and available at all times when there is a patient in the chamber. They should be prepared to enter the chamber if there is a medical emergency.

- **Chamber Operator:**

  The chamber operator operates the chamber according to the prescribed treatment table, and communicates instructions to chamber occupants. They must remain at the control panel at all times. The chamber operator should be trained in the operation of the specific chamber, and be familiar with the emergency action plans.

  The responsibilities of the chamber operator start long before the occupants of the chamber are under pressure. The chamber operator must first check whether all systems are in a safe working condition, including the routine checks and maintenance of various pieces of equipment.

- **Chamber Attendant:**

  The chamber attendant is responsible for the well-being and safety of all the occupants inside the chamber. They monitor the patient and report their response to treatment and any adverse reactions. They provide emotional support and physical care, and assist with hydration and elimination needs. They follow the orders of the physician, and the instructions of the chamber operator.

- **Assistant Operator:**

  Acting as a general assistant, this person logs everything that is happening and keeps a complete written record of all occurrences. They are also available to summon help, fetch anything needed, and to assist the chamber operator. They should be trained to operate the chamber in the event that the appointed operator needs to temporarily leave their station for any reason. They report directly to the chamber operator.

The Chamber Pre-Dive Checks

Chamber Start-Up

The chamber should not be operated by any person unless they are certain it is in an operational condition and that it is safe to use.

To ensure that the chamber is ready for operation, the chamber operator will systematically go through all of the different components using a checklist.

These checks should be completed before each chamber diving operation and a note should be made in the chamber log to this effect and signed by the chamber operator. It is important to remember that even if you ask another person to do the pre-dive checks for you, you as the chamber operator will still remain responsible for these actions.

Each chamber needs to have its own customized checklists, as each chamber installation will be slightly different, and tasks performed in a different order.

Equipment Checks

Ensure that all equipment that may be needed during the treatment is checked and that these devices are in working condition prior to the starting treatment.

Here are a few examples of commonly used items of equipment that are taken into the chamber:

- Blood pressure cuff: A standard manual blood pressure cuff with Velcro is most commonly used inside chambers.

Automatic battery-operated blood pressure monitors should not be taken into the chamber.

- Stethoscope – standard, manual stethoscope
- Hearing protection: Ear protectors should be worn where noise levels are uncomfortable. Where required, these are usually worn on descent as needed during the dive (typically during periods of venting) to protect against hearing damage.
- PPE: Personnel working with patients in the chamber should wear personal protection in accordance with standard precautions.

  Gloves plastic barrier-devices, and surgical masks are generally safe for use under pressure.

Attendant & Patient Checks

The following checks should be performed on all persons entering the chamber:

a. ***No shoes:*** These may bring dirt and possibly oil-bearing compounds into the chamber. Nails in the soles of some shoes can create a spark when they strike the aluminium flooring.

b. ***No unauthorized clothing:*** Only approved clothing (usually 100% cotton scrubs or a suitable blend of not more than 50% polyester), should be worn in the chamber. The clothing should be provided by the chamber facility for each treatment. Any pockets should be sewn shut to avoid the introduction of prohibited items. Underwear sometimes contains synthetic materials and should preferably be avoided. No street clothes should be allowed.

c. ***Equalization:*** All persons that will enter the chamber must be able to equalize their air spaces.

d. ***Medical fitness:*** All personnel entering the chamber to attend a patient must have been cleared as medically fit to dive. They should have documentation on file to validate this. The only exception is in a medical emergency and at the endorsement of the attending physician.

e. ***Previous exposure:*** All persons entering the chamber should declare all previous dives, whether in water or in the chamber, and have completed the required surface interval. The USN treatment tables contain provision for extra oxygen breathing when the surface interval has not yet been completed, but the treating physician makes the decision as to whether that person is allowed to dive or not.

Providing the Chamber Treatment

Overview of Chamber Operating Procedures

The following general chamber operating procedures apply during normal operations:

a. Chamber operator and attendant pre-dive checklists to be completed and signed.
b. All 4 members of the chamber team and the patient to be present and ready to begin.
c. Attendant and patient checks to be performed.
d. Final check on attendant and patient for prohibited items.
e. Attendant and patient enter the chamber together and assume a sitting or lying position, with the patient as visible to the operator as possible
f. Attendant closes the main lock door.
g. Chamber pressurised at the rate and to the depth specified in the prescribed treatment table.
h. Oxygen/air breathing periods carried out as specified in the treatment table.
i. Decompression of personnel to be carried out in accordance with the prescribed treatment table.
j. Personnel post-dive checks performed, and activity restrictions reviewed.
k. Chamber operator and attendant post-dive checklists completed and signed

The following operations may be required during the chamber treatment:

a. Service lock operation
b. Locking in and out of personnel
c. Transfer under pressure
d. Venting the chamber

Chamber Compression

To compress the chamber, the operator needs to ensure that the exhaust valves are in the closed position. T Pressurization valve is then used to increase the pressure in the chamber. The operator must ensure that they are familiar with the diving or treatment table needing to be used. A copy of the prescribed treatment table should be close by.

When performing any chamber procedure, clear instructions must be provided to the inside attendant. Feedback from the attendant is required, so that no miscommunication takes place. The attendant should verbally repeat instructions back to the operator, and then confirm once the action has been performed.

In the following procedures, examples are given in quotes of what operators and tenders might say to facilitate communication. However, you can develop your own phrases that work for your personnel. The importance is that the communication takes place.

It is important that all procedures & occurrences, whether planned or not, including the times when they start and end, are carefully noted in the log by the assistant operator, from the beginning of the initial descent to the arrival back at the surface.

Pressurization procedures:

1. Operator instruction: "*Stand-by: 15fsw(5 msw)*"

   Compression commenced once the attendant has indicated that everything is ready inside the chamber for the dive

   Attendant reply: "*Standing by*"

2. Check that the assistant operator is ready to keep time.

3. Start the stopwatch, check the time and compress the chamber slowly to a depth of approximately 15 fsw (5 msw). Observe/listen attentively for any indication that the descent needs to be stopped. If any problems are experienced at this stage, these should be managed before continuing the dive.
4. Operator: "15 fsw (5 msw) – *All well?*"

   The attendant double-checks that everyone in the chamber is able to equalize.

   Attendant reply: "*All's well*"

   The operator may need to decrease the pressure again until the problem is resolved. Once resolved, compression can continue.
5. Operator instruction: "*Stand-by: 60 fsw (18 msw)*" (or whichever treatment depth is planned)

   Attendant reply: "*Standing by*"
6. Compress the chamber to the treatment depth.
7. Upon reaching the treatment depth, check again that all the occupants are OK.

   Operator: "60 fsw (18 msw) – *All well?*"

   Attendant reply: "*All well*"

The operator has thus performed a safe compression, constantly checking that the occupants are not experiencing any problems.

Note: The operator should always be ready to stop the compression at a moment's notice.

At this stage, the operator should energize the CO_2 scrubber and the environmental control unit if these are fitted to the chamber.

Oxygen Treatment

Begin the oxygen breathing periods and air-breaks as specified in the treatment table:

1. Open the BIBS supply valve and BIBS dump valve on the control panel, if you have not already.
2. Operator instruction: "*On oxygen!*"

   Upon instruction, the attendant opens the valves in the BIBS supply and dump lines on the inside of the chamber, if they are not already open, checks the function of the BIBS mask again, secures the BIBS mask to the injured diver, and reports back to the operator.

   Attendant reply: "Patient on oxygen" The time is then noted by the assistant operator.
3. The operator then maintains the pressure inside the chamber in accordance with the table being used. Additional chamber operating procedures (e.g., lock-ins, venting the chamber, etc. may be performed during these periods, depending on the circumstances
4. When the injured diver needs to take an air-break, in accordance with the table, the operator will again provide this instruction to the occupants:

   Operator instruction: "*Off oxygen!*"

   The attendant takes the injured diver off the oxygen and reports this to the outside.

   Attendant reply: "*Diver off oxygen!*" The time is then noted by the assistant operator.

The attendant may now perform medical checks needed on the patient and report the results. The patient's response during each stage of the treatment should be noted.

These procedures are repeated for each oxygen breathing period and corresponding air-break. The only other instruction provided to the inside is when a treatment depth change is needed in accordance with the table.

Additional Chamber Operating Procedures

The following procedures may be required during the normal chamber operating procedures:

- Venting the chamber
- Lock-in and lock-out (personnel and equipment)

Venting the Chamber:

Venting the chamber with fresh air is one of the ways in which the chamber atmosphere can be controlled. It is used when the O_2 or CO_2 content of the chamber is too high, as well as for cooling the chamber down, especially after the initial compression phase, which generates heat. Venting the chamber basically means that you want to exchange the air in the chamber, but keep the pressure constant.

To vent the chamber, you need to open the ML exhaust valve and ML pressurization valve simultaneously to provide equal rates of pressurization and exhaust. The air in the chamber will thus be exchanged without changing depth. The air entering the chamber is being decompressed, now at a lower pressure in the chamber than in the gas banks, causes the air to cool. Venting will thus cool the chamber down.

Venting the chamber normally produces quite a lot of noise. The occupants of the chamber should wear hearing protection while the chamber operator is venting the chamber.

Lock-in and lock-out:

Personnel and/ or equipment can be locked into or out of the chamber during the treatment. There are only two types of locks on the chamber that are suitable for this purpose and both of them work similarly. These are the entry and the service (or medical) locks. The chamber operator controls the lock-in and lock-out procedure and provides instructions to everyone involved.

The lock-in or lock-out procedures may be initiated upon the request of the attendant (e.g., needing equipment), or it may be necessary in an emergency , i.e., if you need to lock in additional medical personnel.

Lock-in procedures using the entry lock:

For a lock-in procedure the chamber attendant will be in the Main Lock (ML) under pressure. The Entry Lock (EL) will not be pressurized at this stage. It is still at the surface, at atmospheric pressure. The operator places the equipment and/or personnel to be locked into the EL and closes the man-way door.

Inform the attendant that you are about to dive the EL.

Close the EL exhaust valve and open the EL pressurization valve to increase the pressure in the EL.

As soon as the EL pressure is close to the ML pressure, the following commands are provided to the attendant, starting with: "*stand by to equalize the entry lock*" – the chamber attendant acknowledges this command by saying "*standing by*".

1. Operator command: "*Equalize the entry lock*".

   Upon command, the chamber attendant opens the EL equalization valve to equalize the pressure between the ML & EL. If not, the ML dock will open anyway once the pressure in the EL is equal with the pressure in the ML.

   Attendant reply: "*equalizing the EL*".

   The operator needs to ensure that the pressures of both locks remain constant at the depth of the table being used.

2. Operator command: "*Open ML man-way door*".

This means that the lock pressures have equalized You can verify this with the pressure gauges on the control panel. The attendant then opens the ML man-way door.

Attendant reply: "*ML man-way door opened for transfer*"

3. The attendant can now transfer the equipment to the ML. After this had been done, the attendant informs the operator.

   Attendant reply: "*Equipment transferred*".

4. Operator command: "*Close ML man-way door*"

   Upon command, the chamber attendant closes the ML man-way door. The door should be locked or held tightly closed to ensure a tight seal.

   Attendant reply: "*ML man-way door closed and locked*".

5. Operator command: "*Close EL equalization valve*".

   Upon command, the chamber attendant closes the EL equalization valve.

   Attendant reply: "*EL equalization valve closed*".

6. The operator can now safely surface the EL again.

If personnel are being locked in, the same procedures should be followed as for the initial compression. There should thus be clear communication between the operator and the personnel in the entry lock, there should the same safety check as with a patient at a depth of approximately 15 fsw (5 msw) and compression should be halted if any problems are experienced.

Lock-out procedures using the entry lock:

The following procedure should be followed when using the entry lock for lock-out. Note again that the chamber operator needs to provide the instruction for each of these actions to the chamber attendant.

For a lock-out procedure the chamber attendant will be in the ML under pressure and the EL will be at equal pressure, with the man-way door opened.

The lock-out procedures will start with the command: "*transfer to the EL*"

1. Operator command: "*Transfer to the EL*"

   Upon command, the chamber attendant transfers all personnel and/or equipment that should be locked out to the EL.

   Attendant reply: "*Personnel and/ or equipment transferred to EL*".

2. Operator command: "*Close ML man-way door*"

   Upon command, the chamber attendant closes the ML man-way door. The door should be locked to ensure a tight seal.

   Attendant reply: "*ML man-way door closed and locked*".

3. Operator command: "*Close EL equalization valve*".

   Upon command, the chamber attendant closes the EL equalization valve.

   Attendant reply: "*EL equalization valve closed*".

At this stage, the chamber operator will surface the EL and remove the personnel and/ or equipment from the EL. If personnel have been locked out, they need to receive the post-dive checks. They should remain at the chamber until the treatment is completed. They should also receive the post-dive restrictions like any other attendant.

Lock-in procedures using the service lock from the inside:

The following procedure should be followed when using the Service Lock (SL) for lock-in. Note again that the chamber operator needs to provide the instruction for each of these actions to the chamber attendant.

The chamber attendant will be in the Main Lock (ML) under pressure. The SL will not be pressurized yet. Clear communication between the chamber operator and the chamber attendant is necessary to ensure safe transfer of items.

After all the items are placed in the service lock, the lock door can be closed. It is now ready for pressurization. Inform the attendant that you are about to pressurize the service lock.

The chamber attendant lock-in procedures will start with the command: "*stand by to take the service lock*" – This command is provided as soon as the pressure in the service lock is almost equal to the pressure inside the chamber. The chamber attendant acknowledges this command by saying "*standing by*".

1. Operator instruction: "*Equalize the lock*"

   Upon instruction, the chamber attendant will open the SL equalization valve to equalize the pressures between the ML and SL.

   Attendant reply: "*Equalizing the SL*"

2. Operator instruction: "*Take the lock*"

   Upon instruction, the chamber attendant will take the lock, undog or unlatch the SL and open the SL door.

   Attendant reply: "*taking the lock*"

3. The chamber attendant removes the equipment locked in.

   Attendant reply: "*equipment transferred*

4. Operator instruction: "*Close the lock*"

   Upon instruction, the chamber attendant closes the SL door, then locks and dogs/latches it securely.

   Attendant reply: "*SL locked and dogged/latched*"

5. Operator instruction: "*Close the lock equalization valve*"

   Upon instruction, the chamber attendant closes the service lock equalization valve.

   Attendant reply: "*Lock equalization valve closed*"

   The chamber operator can then surface the SL again.

Lock-out procedures when using the service lock from the inside:

The lock-out procedure using the SL is almost exactly the same as the lock-in procedure.

For a lock-out procedure, the chamber attendant will be in the Main Lock (ML) under pressure. Depending on what needs to be locked out, the chamber operator may need to lock in containers. For instance, if sharp instruments ,e.g., injection needles, or something wet or containing liquid need to be locked out, the chamber operator may need to lock in a plastic container or bag.

The chamber attendant lock-out procedures will start with the command: "*stand by to equalize the service lock*". This command is provided as soon as the pressure in the service lock is almost equal to the pressure inside the chamber. The chamber attendant acknowledges this command by saying "*standing by*".

1. Operator instruction: "*Equalize the lock*"

   Upon instruction, the chamber attendant will open the SL equalization valve to equalize the pressures between the ML and SL.

   Attendant reply: "*Equalizing the lock*"

2. Operator instruction: "*Take the lock*"

   Upon instruction, the chamber attendant will take the lock, undog/unlatch the SL and open the lock door.

   Attendant reply: "*taking the lock*"

3. The chamber attendant now places all of the equipment to be locked out in the SL. Ensure that no containers are closed, as this may cause overpressurization of the container which could burst.

   Attendant reply: "*equipment transferred to SL*".

4. Operator instruction: "*Confirm all equipment is safe*"

   Upon this instruction, the chamber attendant needs to double-check that no closed containers or any other dangerous materials are present in the lock that may injure the personnel on the outside.

   Attendant reply: "*All equipment safe*"

5. Operator instruction: "*Close the lock*"

   Upon instruction, the chamber attendant closes the SL door, then locks and dogs/latches it securely.

   Attendant reply: "*SL locked and dogged/latched*"

6. Operator instruction: "*Close the lock equalization valve*"

   Upon instruction, the chamber attendant closes the service lock equalization valve.

   Attendant reply: "*Lock equalization valve closed*"

The chamber operator can then surface the SL.

Decompressing the chamber:

After completion of the deeper portion of the treatment table, or at the end of the treatment, the chamber needs to be decompressed to the shallower depth or surfaced. The following example assumes that a USN TT6 had been used and there is a decompression from 60 fsw (18 msw) to 30 fsw (9 msw), in the middle of the treatment table:

1. Operator instruction: "*Stand-by* 30 fsw (9 msw)

   Attendant reply: "*Standing by*"

2. At the correct timing on the stop-watch, the operator opens the exhaust valve to reduce the pressure in the chamber at the ascent rate indicated in the TT. The operator should be ready to stop the ascent at a moment's notice if the patient or attendant suddenly experience symptoms, e.g., barotrauma. The operator may need to increase the pressure again and return to the previous depth of the table until the problem is resolved. Be ready to lock in personnel and/or equipment that may be needed inside.

3. When arriving at 30 fsw (9 msw), check whether the occupants are OK

   Operator instruction: "*All well?*"

   The attendant checks all occupants and the equipment and reports back

   Attendant reply: "*All's well!*"

After reaching 30 fsw (9 msw), the “on oxygen” and “off oxygen” procedures need to be followed again, in accordance with the treatment table. The operator should at this stage already know whether the attendant needs to go onto oxygen. The attendant’s requirements for oxygen breathing depend on the depth and duration of the treatment table, as well as the altitude at which treatment is provided. The following example from the US Navy diving manual, provides a guideline:

Table 21-6. *Tender Oxygen Breathing Requirements.*[1]

		Altitude		
Treatment Table (TT)		Surface to 2499 ft.	2500 ft. – 7499 ft.	7500 ft. – 10,000 ft.
TT5[2]	without extension	:00	:00	:00
	with extension @ 30 fsw	:00	:00	:20
TT6[2]	up to one extension @ 60 fsw or 30 fsw	:30	:60	:90
	more than one extension	:60	:90	:120
TT6A[2]	up to one extension @ 60 fsw or 30 fsw	:60	:120	:150[3]
	more than one extension	:90	:150[3]	:180[3]
Note 1	All tender O_2 breathing times in table are conducted at 30 fsw. In addition, tenders will breathe O_2 on ascent from 30 fsw to the surface.			
Note 2	If the tender had a previous hyperbaric exposure within 12 hours, use the following guidance for administering O_2: For TT5, add an additional 20 minute O_2 breathing period to the times in the table. For TT6 or TT6A, add an additional 60 minute O_2 breathing period to the times in the table.			
Note 3	In some instances, tender's oxygen breathing obligation exceeds the table stay time at 30 fsw. Extend the time at 30 fsw to meet these obligations if patient's condition permits. Otherwise, adminster O_2 to the tender to the limit allowed by the treatment table and observe the tender on the surface for 1 hour for symptoms of DCS.			

A diving medical doctor may alter these requirements.

The same procedures used during the decompression from 60 fsw (18 msw) to 30 fsw (9 msw) are used for the decompression from 30 fsw (9 msw) to the surface.

When the chamber has reached the surface, a “hissing sound” may be heard as the pressure inside the chamber equalizes with the atmospheric pressure. The man-way door can now be opened.

Post-dive procedures

Personnel Post-Dive Checks

Once the door is open, if no symptoms are experienced, the occupants may exit the chamber and stay nearby for their post-dive checks.

The chamber operator performs the following checks on the occupants,

and assures that they are aware of post-dive restrictions:

- Check whether they are all OK
- Neurological assessment

The chamber operator notes in the log the results of the post-dive checks.

The diving medical doctor on site will usually re-assess the patient after treatment. The chamber operator must ensure that, even if the injured diver is removed from the immediate area to an area where the assessment is performed, the patient has received information regarding post-dive restrictions that are highlighted in the following section.

Post-dive restrictions:

1. ***Observation period:***

   The occupants should remain in the immediate vicinity within 30 minutes travel time of the chamber for a period of 4 hours and remain within 60 minutes of the chamber for 20 hours following this.

   The occupants should not be alone for 24 hours – someone should be able to check them for signs/ symptoms.

2. ***Altitude exposures:***

   The attendant is not allowed to fly or go to altitude, e.g., mountain passes, for the next 24 hours. A patient that was treated is usually advised not to fly or go to altitude for the next 72 hours. However, the diving medical doctor should recommend the waiting period interval and may modify it.

3. ***Dive exposures:***

   The attendant may not dive again for the next 24 hours. The injured diver may only dive again after clearance by a diving medical doctor.

4. ***Hot showers and exercise:***

   The occupants should not take a hot shower for the next 6 hours.

The occupants should not do strenuous physical exercise for the next 12 hours.

5. ***Contact details:***

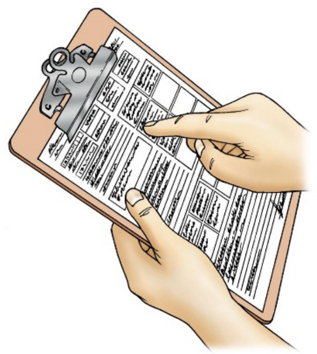
   The occupants should be provided with a card or sheet that lists these restrictions and contains the contact numbers of the chamber personnel on call, in case they develop symptoms.

A diving medical doctor may increase or reduce these restrictions.

Chamber post-dive checks

Chamber shut-down:

To ensure that the chamber is properly shut down after operation, the chamber operator will systematically go through all the different components using a checklist.



These checks should be completed after each chamber diving operation and a note should be made in the chamber log to this effect and signed by the chamber operator. It is important to remember that even if you ask another person to do the post-dive checks for you, you as the chamber operator will remain responsible for these actions.

Each chamber needs to have its own customized checklists, as each chamber installation will be slightly different, and tasks performed in a different order.

Decision to modify the treatment table

The following factors, and possibly others not listed, will influence the decision to modify the treatment table:

- The treatment table currently in use
- The situation being faced
- The condition of the patient and attendant
- The response of the patient to treatment
- Information provided by the chamber attendant
- Information provided by the doctor

Only a doctor is allowed to modify the treatment table, but the chamber operator remains responsible.

The following steps may be taken when a doctor changes a diving table for medical or other reasons:

1. The doctor informs the chamber operator of the intention to change the treatment table.
2. The chamber operator is provided with enough information to make an informed decision:
   a. The medical reason for changing the treatment table
   b. Oxygen Toxicity Units were calculated for the injured diver
   c. Decompression obligations of the attendant(s) were taken into account (a general safety measure may be to put them on oxygen)
3. The changed table should be provided in writing to the chamber operator.
4. The operator needs to decide whether the changes are possible – e.g.
   a. Is there enough oxygen and air available for a longer or deeper table?
   b. Do you have the gas mixing capabilities (if required)
   c. Do you have operational back-up for a longer treatment e.g., extended tables.

The chamber operator may use the table alteration sheet that is provided in the toolbox.

Examples of chamber emergencies that might force you to change the treatment table:

1. You cannot descend as planned
   a. Occupants cannot equalize (barotrauma)
   b. Equipment problems
2. You cannot continue the breathing gas
   a. Oxygen toxicity
   b. Problem with gas supply
3. You cannot ascend as planned
   a. Pneumothorax
   b. Barotrauma – reverse block
   c. Equipment problems

Problems to expect during a Chamber Treatment

Problems Descending

If any of the occupants experience a problem during the descent, the descent should be stopped immediately. The most common problem experienced during the descent is difficulty to equalize the ears or another gas space. Try the following manoeuvres:

- Ascend until symptoms resolve and check equalization ability at the shallower depth. The attendant can coach on various equalization techniques. Slowly continue with the descent when the patient can equalize. Repeat as necessary.
- If the patient is not able to equalize at all, after the above has been repeatedly tried, notify the diving medical doctor who can order a decongestant nasal spray to try. If after all interventions have been tried, and the patient is still not able to equalize at all, the chamber should be surfaced. If the person needs recompression therapy, an emergency myringotomy can be performed. But this is rarely necessary, most patients will eventually be able to equalize using the above techniques.
- If it is the attendant who is unable to equalize, they will need to be relieved by a backup attendant.

The patient is not affected by this increased time at depth from a treatment point of view, because the treatment table only starts once the treatment depth has been reached. The diver will be breathing oxygen during the treatment, so no additional inert gas will be absorbed unless this period is extensive.

Because of additional time spent at depth, the chamber operator should consider the need for the attendant to breathe additional oxygen towards the end of the treatment. They should consult with the diving medical doctor.

Problems at Depth

Oxygen toxicity: As important as oxygen is in our lives, it can also have negative side effects in high doses. The human body is designed to breathe oxygen at a partial pressure of 0.21 atm (21% of 1 atm); inside the chamber this will increase considerably. On a standard HBO treatment, the patient breathes 2.0 – 2.4 ATA oxygen, while during diver recompression this can increase up to 2.8 ATA. Increased oxygen partial pressure can affect the central nervous system, while prolonged exposure to high oxygen concentrations can cause damage to the pulmonary system.

CNS oxygen toxicity:

CNS oxygen toxicity can only happen during hyperbaric conditions when the oxygen partial pressure is elevated above 1.4 ATA. It is believed that excess oxygen in the body affects the transmission of signals between the neurons (brain cells) The exact reason, however, is still unknown.

The chamber attendant should constantly monitor the diver for the early signs and symptoms of CNS oxygen toxicity. It is important to note that some patients may be more sensitive to oxygen toxicity than others. Some patients may be more susceptible such as with an injury to the brain, e.g., cerebral DCS or a Cerebral Arterial Gas Embolism.

At the first signs of possible oxygen toxicity, **oxygen is immediately removed,** chamber personnel and the doctor are notified immediately, and the patient breathes chamber air. Wait a minimum of 15min after the signs and symptoms have subsided before putting the patient back on oxygen again. Should the signs and symptoms not subside, or they develop again, consult the doctor about modifying the treatment tables. The doctor may decide to decrease the depth, shorten oxygen periods or lengthen air-breaks. The doctor may have to lock into the chamber to more thoroughly assess the patient, assist the attendant, and/or administer medications.

Should an oxygen seizure occur, discontinue oxygen and protect the patient from harm, such as padding with pillows and blankets around the head and body. Do not attempt to insert a bite block. After the convulsions have subsided, the attendant examines the patient for injuries.

Early signs and symptoms of CNS oxygen toxicity:

- **V** – Vision (Tunnel vision, spots, flickers)
- **E** – Ears (Tinnitus – ringing in the ears)
- **N** – nausea (Nausea with or without vomiting)
- **T** – Twitching (muscle twitching – most often the lips, hands)
- **I** – Irritability (Unexplained anxiety/ irritability)
- **D** – Dizziness (light-headedness)
- **C** – Convulsions (Often the first sign)

Signs and symptoms of CNS oxygen toxicity can progress very rapidly to convulsions, often within seconds, so it is important to act quickly.

Pulmonary oxygen toxicity:

This form of oxygen toxicity is caused by prolonged respiration of high oxygen percentages, regardless of partial pressure, so it can occur in normobaric as well as hyperbaric environments. It is not frequently seen during commonly used treatment tables such as USN TT6 and USN TT5, but multiple or extended HBO sessions increase the risk.

The signs and symptoms are a dry throat, coughing, substernal burning sensation, shallow/rapid breathing, chest pain and dyspnoea even at rest. The onset is slow, and the patient will usually complain about discomfort first. If this occurs during a treatment, oxygen periods may be shortened, or air-breaks lengthened by the doctor

Problems Ascending

These problems are rare, but the chamber attendant should be ready for this eventuality.

Examples of problems on the descent are reverse block of the ears, pneumothorax, medical equipment problems, return of DCS symptoms.

Remember that the patient is on oxygen, so an overstay at depth has little effect on them, but it does produce the potential for decompression problems for the chamber attendant. If there are problems and the occupants need to overstay the bottom time, remember to provide the chamber attendant with additional oxygen breathing periods, to prevent decompression sickness. You may even decide to prolong the table so the attendant can have a longer oxygen breathing period.

Chamber Emergencies

Chamber Emergency Action Plans

No matter how well you plan your chamber dive; there will still be a possibility of an unforeseen emergency. Emergency action plans that are specific to your facility must be compiled and developed, and your entire team trained, and live drills carried out.
The following emergency action plans are typical in hyperbaric chambers but must be customized to your particular hyperbaric facility.
Each person should know their responsibilities in the case of an emergency. The responsibility of the assistant operator is always to document all occurrences along with the exact time, and assist the operator as directed. Your emergency action plans should be regularly practised as emergency drills. When an emergency occurs, there is no time to look for the file where the EAPs are kept. There is only time to act!

Operational and Technical Emergencies

Fire Inside the Chamber

Chamber Operator	Tender Inside	Doctor
• Activate fire deluge if available • Switch BIBS from oxygen to air and advise all occupants to don BIBS. • Close all oxygen valves. • Disconnect the main electrical supply. • Activate fire alarm and alert the local fire department. • Decompress chamber as quickly as possible. • Evacuate occupants. • Notify doctor and re-evaluate tender decompression.	• Notify chamber operator and request air to BIBS • Put all occupants on BIBS • Extinguish fire with hand-held hose or deluge if possible • Evacuate patient when chamber reaches surface.	• Determine need to decompress or continue dive • Assist in evacuation of chamber if necessary • Assess chamber occupants and treat for injuries

Fire in the Facility, Outside of the Chamber

Chamber Operator	Tender Inside	Doctor
• Switch BIBS from oxygen to air. • Activate fire alarm and alert the local fire department • Close all oxygen valves. • Shut down compressors if smoke could contaminate air source. • Switch primary air supply back up supply if needed. • Don emergency breathing apparatus if needed. • Extinguish fire if possible. • Determine if treatment should continue. • Decompress chamber if necessary. • Notify Doctor and manager. • Prepare report.	• Reassure the patient • Prepare for possible decompression. • Monitor occupants • Evacuate occupants if required	• Determine if treatment should continue • Assess occupants • Assist chamber operator • Communicate with nearest chamber for possible recompression of occupants…

Accidental Activation of the Fire Suppression System

Chamber Operator	Tender Inside	Doctor
• Secure deluge. • Lock in dry towels, blankets and clothing. • Drain bilge, monitor depth and adjust treatment profile as directed by doctor.	• Notify chamber operator. • Reassure patients. • Provide patient with dry towels, blankets and clothing • Assist patients to dry off and change clothing • Wipe chamber surfaces dry…	• Supervise decompression if necessary.

Loss of Primary Air

Chamber Operator	Tender Inside	Doctor
• Secure air supply and stop venting. • Switch to backup air supply. • Turn on backup compressor. • Notify tender and doctor of the occurrence. • Attempt to identify and correct the problem. • Monitor chamber oxygen level closely.	• Reassure patient. • Monitor occupants for symptoms of carbon dioxide toxicity: • *Shortness of breath,* • *Panting,* • *Headache, etc.* • Be prepared for modification of treatment table or decompression.	• Determine if treatment needs to be modified or aborted. • Assess occupants as needed.

Loss of Back-up Air Supply

Chamber Operator	Tender Inside	Doctor
• Notify tender & doctor. • Put all occupants on oxygen and prepare for decompression.	• Keep patient calm. • Put all occupants on BIBS. • Prepare for decompression.	• Discuss decompression profile with operator. • Communicate with nearest chamber for possible recompression. • Assess occupants as needed.

Loss of Oxygen Supply

Chamber Operator	Tender Inside	Doctor
• Switch to emergency backup system. • Notify the doctor. • Determine cause and correct it if possible. • Be prepared for modification of treatment table or decompression.	• Notify chamber operator. • Remove patient BIBS. • Give manual breathing support for ventilated patients. • Determine if cause is inside chamber. • Correct if possible. • Be prepared for modification of treatment table or decompression.	• Determine if treatment needs to be modified or aborted.

Loss of Back-up Oxygen Supply

Chamber Operator	Tender Inside	Doctor
• Switch BIBS to air. • Notify the doctor. • Prepare for air decompression.	• Keep patient calm. • Remove BIBS. • Prepare for air decompression.	• Discuss decompression profile with operator. • Communicate with nearest chamber for possible recompression. • Assess occupants for DCS.

Rapid Decrease in Chamber Pressure

Chamber Operator	Tender Inside	Doctor

• Restore chamber to scheduled treatment depth as rapidly as can be tolerated by occupants, if possible.
• If return to treatment depth is not possible:
  • Open chamber supply to stop or slow ascent as much as possible.
  • Inform all occupants BIBS.
  • Close all exhaust valves at shell and console.
  • Turn on all compressors and use emergency backup air if available.
  • Notify doctor.
  • Be prepared for modification of treatment table or decompression.
	• KEEP PATIENT CALM.
	• All occupants go on oxygen.
	• Determine source and secure if possible. (A wet towel in breach of pressure boundary may slow the ascent).
	• Close all inside exhaust valves.
	• Assist in evacuation.
		• Determine if treatment needs to be modified or aborted.
		• Determine if precautionary treatments necessary for occupants.
		• Evaluate occupants after decompression.

Rapid Increase in Chamber Pressure

Chamber Operator	Tender Inside	Doctor
• Secure air supply to chamber. • Inform occupants to remove BIBS. • Restore chamber to the scheduled treatment depth at a rate not exceeding 30 ft/minute (9 m/minute). • Notify doctor. • Continue with treatment as directed by the doctor.	• Notify chamber operator. • Remove BIBS. • Close inside supply air supply valve if available. • Assess chamber occupants for barotraumas. • Reassure patient.	• Determine if treatment needs to be modified or aborted. • Determine if chamber occupants suffered barotraumas. • Lock into chamber if necessary to treat barotraumas. • Assess patients after decompression.

Contaminated Air Source

Chamber Operator	Tender Inside	Doctor

• Switch to back up air supply and do a continuous fast vent.
  • Attempt to isolate source by having the assistant operator do the following:
  • Check compressor room and compressors.
  • Sample air from LP volume tank for odor/contamination.
  • Check for external contamination around air intakes.
• If volume tanks are contaminated, ensure that treatment can proceed on HP back up air supply.
• If source was from outside and is no longer present, drain volume tanks through drains and recompress volume tanks.
• If odor remains after vent, put all occupants on oxygen masks and decompress as described by doctor
• Prepare report.
	• Notify chamber operator and attempt to describe odor.
	• If odor remains after vent, notify operator and put all occupants on BIBS.
	• Determine if it is an inside source and remove source if possible.
	• Assist with chamber evacuation if necessary.
	• Assist chamber operator in determining the source.
		• Assist in determining contamination source.
		• Determine whether dive should proceed.
		• Supervise decompression if necessary.
		• Evaluate occupants upon exit from chamber.

Loss of Power

Chamber Operator	Tender Inside	Doctor
• Switch on emergency lighting. • Stop any continuous vents and do short vents only if required. • Notify doctor. • Determine time/amount of remaining air. • Monitor chamber oxygen level. • Start backup generator if available.	• Reassure patient. • Use portable lamp if available. • Prepare for decompression if necessary.	• Prepare for decompression if air supply runs out.

Loss of Communication

Chamber Operator	Tender Inside	Doctor
• Use sound powered phone or written communication via viewports. • Check all connections. • Check batteries.	• Notify Chamber Operator. • Check inside connections. • Use sound powered phone or written communication via view ports.	• Use sound powered phone or written communication via view ports.

Hyperbaric Chamber Medical Emergencies

CNS Oxygen Toxicity Seizure

Chamber Operator	Tender Inside	Doctor
• Maintain depth. • Switch BIBS to air. • Notify Doctor immediately. • Do not change depth until tonic phase is over and normal breathing resumes. • Note time the patient is off oxygen. • Be prepared for modification of treatment table or decompression. • Lock in personnel if needed. • Re-evaluate tender decompression.	• Remove BIBS. • Notify chamber operator. • Protect patient from injury. • Keep patient off oxygen for 15 minutes or as directed by the doctor.	• Supervise patient care. • Determine if treatment needs to be modified or aborted. • Be prepared to lock into the chamber.

Pulmonary Oxygen Toxicity

Chamber Operator	Tender Inside	Doctor
• Notify doctor immediately. • Be prepared for modification of treatment table or decompression. • Lock in personnel if needed. • Revaluate tender decompression.	• Notify chamber operator if patient has symptoms. • Take vital signs and monitor symptoms. • Prepare to remove BIBS from patient if instructed.	• Supervise patient care. • Determine if treatment needs to be modified or aborted. • Be prepared to lock into the chamber.

Omitted Decompression

Chamber Operator	Tender Inside	Doctor
• Notify doctor immediately. • Prepare to recompress on USN TT5 if no symptoms are present (per DMO order). • Prepare to recompress on USN TT6 if symptoms are present (per DMO order). • Make report as to why decompression was omitted.	• Monitor occupants with omitted decompression for symptoms of DCS. • Prepare to be recompressed on USN TT5 or TT6.	• Assess occupants with omitted decompression for symptoms of DCS. • If symptomatic, may treat with USN TT6 or equivalent. • If asymptomatic, may treat with USN TT5 or equivalent. • Start recompression as soon as possible.

Cardiac Arrest

Chamber Operator	Tender Inside	Doctor
• Maintain chamber depth. • Notify doctor immediately. • Prepare to lock in doctor and additional personnel. • Prepare to lock in supplies and equipment. • Prepare to decompress chamber as directed by doctor. • Activate the emergency medical system.	• Notify chamber operator. • Remove padding from underneath patient or slide in backboard. • Establish airway. • Begin CPR in the absence of respiration and heartbeat. • Do not stop resuscitation effort. • Prepare for chamber decompression.	• Give chamber operator instructions for decompression. • Prepare to lock into chamber to assist with resuscitation efforts. • Assess other chamber occupants for need for recompression after arrival at surface.

Pulmonary Barotrauma / Pneumothorax

Chamber Operator	Tender Inside	Doctor
• Stop chamber ascent or descent. • Notify doctor immediately. • Prepare to lock in doctor and additional personnel. • Prepare to lock in supplies and equipment. • Prepare to decompress chamber as directed by doctor.	• Notify chamber operator of occurrence. • Monitor condition of patient. • Assist doctor as directed. • Help make patient as comfortable as possible.	• Lock into chamber. • Insert Heimlich valve or large bore needle while still under pressure. • Chest tube placement can be performed under controlled conditions on the surface.

Ear / Sinus Barotrauma Upon Descent or Ascent

Chamber Operator	Tender Inside	Doctor
• Stop chamber descent or ascent. • Ascend or descend the chamber in small increments until the pressure is relieved. • Lock in medications and/or personnel as needed. • Slowly continue ascent or descent when tender gives the OK signal.	• If patient shows signs of discomfort, notify chamber operator to stop the ascent or descent. • Work with patient in pressure equalization techniques. • Have patient sip water or use nasal spray if ordered by the doctor. • Let chamber operator know when it is OK to slowly continue. • Have affected occupant checked by the doctor upon exiting the chamber.	• Order nasal decongestant spray as needed. • Prepare to perform emergency myringotomy if it is decided that the treatment must continue. • Check affected occupant upon exiting the chamber.

Vomiting

Chamber Operator	Tender Inside	Doctor
• Stop chamber descent or ascent. • Notify doctor. • Lock in medications and/or personnel as needed. • Lock in containers and clean linens as needed. • Continue chamber descent or ascent when vomiting ceases. • Prepare to decompress chamber if directed by doctor.	• Notify chamber operator of occurrence. • Administer medications as ordered. • Assist doctor as needed. • Help patient clean up and make as comfortable as possible	• Order medications as needed. • Prepare to lock in to chamber if needed.

Claustrophobia

Chamber Operator	Tender Inside	Doctor
• Notify doctor. • Prepare for modification of treatment table or decompression. • Prepare to lock in medications of ordered. • May have family provide support via chamber communication system.	• Notify chamber operator. • Provide reassurance, reinforce benefits of treatment. • Attempt distraction, i.e., soft music, calm movie. • Help make patient as comfortable as possible. • Administer medications if ordered.	• Communicate with patient as needed, provide reassurance. • Order medications as needed. • Determine if treatment needs to be modified or aborted

Uncooperative / Aggressive Patient

Chamber Operator	Tender Inside	Doctor
• Notify doctor. • Prepare to lock in additional personnel. • Prepare to lock in medications if ordered. • Prepare to decompress chamber if necessary. • May have family provide support via chamber communication system.	• Notify chamber operator. • Attempt to calm patient. • Provide reassurance, reinforce need for treatment. • Administer medications as ordered. • Attempt distraction, i.e., soft music, calm movie.	• Order medications as needed. • Determine if treatment needs to be modified or aborted. • Communicate with patient as needed, provide reassurance, reinforce need for treatment.

Chamber Fires

A fire in the hyperbaric chamber and the potential resulting explosion of the chamber has been a tragic feature of the hyperbaric industry over many years.

Some basic knowledge of the dynamics of chamber fires is required in order to be able to prevent these from happening.

The Fire Triangle

For any fire to start and to be maintained, three important components need to be present, namely oxygen, fuel, and an ignition source.

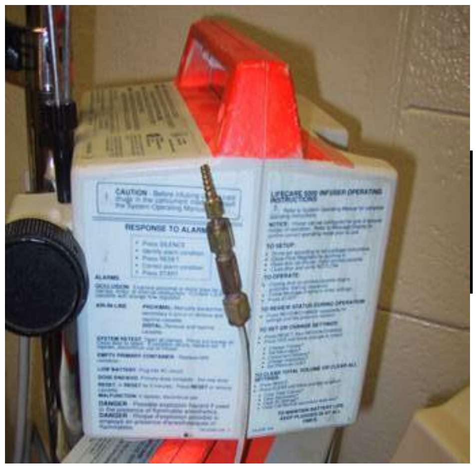
If any one of these is removed, there is no risk of a fire.

In the hyperbaric chamber, at least two of these components are always present, oxygen and fuel.

To prevent a chamber fire, is essential to exclude any ignition sources.

Irrespective of the partial pressure of the oxygen, the percentage of oxygen inside the chamber should always be kept below 23.5%.

Any equipment taken into the chamber should be certified as safe for hyperbaric applications, and comply with the regulations contained in publications such as NFPA (the National Fire Protection Association) 99, chamber 14).



Equipment may need to be modified to prevent the build-up of oxygen in or around electrical parts. This can be achieved through an inert gas purge inside the equipment.

The following are all ignition sources that should be prohibited from entering the chamber:

- Heat sources: smoking, open flames, hot objects, warming devices, warming patches
- Electrical sources: cell phones, sparking toys, personal entertainment devices.
- Flammable gases and liquids: alcohol, lighter fluid, alcohol and acetone.
- Personal products: hairspray, hair oils, body oils, lotions, cosmetics, perfumes.

Additional electrical rules include:

- No open or arcing electrical switches
- No brushed or overheated electrical motors
- No heated surfaces of lamps or tubes
- Maximum voltage: 28 V_{DC}
- Maximum power 48W at 12 V_{DC} or 24 $_{VDC}$
- Non-insulated conductors: 0.5 Amps
- Any heat source: <85ºC.
- No electrical thermostats

Materials such as such as silk, wool, synthetic cloth, exposed foam, unapproved clothing, and shoes should be prohibited. As a general rule, do not allow quantities of burnable materials, such as paper, to be stored in the chamber. These include books and other reading matter.

Some items are more hazardous than others, e.g., the ink used for newspaper printing is readily flammable.

Complications as a result of a Chamber Fire

- Depletion of oxygen for breathing
- Overheated breathing gases
- Production of toxic gases & products (especially CO)
- Burns (combustion of human tissue)
- Potential over-pressurization of the pressure vessel

Reaction time is always limited in trying to get any fire under control.

Oxygen Safety

Oxygen is a colourless, odourless, and tasteless diatomic gas at standard temperature and pressure. It is a strong oxidizing agent, reacts with most other elements and compounds. and to supports combustion when handled improperly.

In handling with oxygen, there is always the possibility of a fire or explosion risk. Spontaneous combustion is possible where high concentrations of oxygen come in contact with hydrocarbons (e.g., oils) or any other volatile materials (alcohol, acetone).

However, it is also essential sustain life, and is the primary treatment drug. It will therefore always be present at recompression facilities.

It is important that at least the following safety procedures are followed when handling oxygen cylinders.

Oxygen Storage

1) All oxygen cylinders should be kept in an “oxygen area” and clearly marked with signs indicating a fire & explosion risk.
2) The oxygen area should be in a well-ventilated open-air environment with no electrical fittings in the immediate vicinity
3) The oxygen area should be separate from other gas cylinder storage areas.
4) Smoking and other ignition sources should be prohibited in the oxygen area.
5) No petroleum-based or volatile products should be allowed close to the oxygen area.
6) Oxygen cylinders should be firmly secure to prevent them from falling over.
7) Any and all fittings, hoses, or attachments likely to come in contact with oxygen must be clean and oil- free.
8) All cylinders should be color-coded correctly.

Oxygen Cylinder Requirements:

All oxygen cylinders should arrive from the manufacturer labelled with the gas, correctly colour coded (green in the US, white shoulder in the rest of the world), and with a certificate of analysis.

The neck area of the cylinder should display the specifications required by relevant jurisdiction, e.g., US Department of Transportation (DOT), or ISO 17239. This should typically include:

1. Maximum working pressure)
2. Test pressure
3. Cylinder thread
4. Manufacturer and assigned serial number
5. Capacity
6. Inspector’s stamp
7. Date of initial qualification and dates of any subsequent recertification

Recertification is typically required every 10 years, including hydrostatic testing.

Oxygen Safety Guidelines

- **Always** vent some gas before connecting HP whips.
- **Always** keep oxygen connections clean.
- **Always** use a clean wrench when changing oxygen cylinders.
- **Never** leave an oxygen hose or fitting exposed to possible contamination.

All filled oxygen cylinders should be tested for oxygen when received. Cylinders must be properly marked with following information before connecting online:

- Date
- Oxygen percentage
- Cylinder pressure
- Placement of Green “In use” or Red “Empty” tags
- Initials of testing staff

Adiabatic Compression: This process is described in the section on Physics of the Hyperbaric Environment. It can happen when opening an oxygen cylinder The only way to avoid this is to open all oxygen valves **s-l-o-w-l-y**.

Unless specifically trained, do not transfer oxygen from a full bottle to an empty one.

- **Always** secure oxygen any high-pressure cylinders when either empty or full.
- **Never** move an oxygen cylinder without the protective cap or shroud.
- **Neve**r move an oxygen or any high-pressure cylinder with a regulator attached.
- **Never** attempt to move an oxygen cylinder unless trained and able to so.

Meals and Medications

During prolonged treatment periods, the occupants of the chamber may require meals or drinks to be locked into the chamber. When introducing food and drinks into the chamber, the prohibited items list also applies. e.g., oil-based salad dressings, foam containers.

Food items in takeout containers may need to be transferred to non-disposable dishware.

Bottle tops should be loosened to allow the pressure inside to equalize.

Sealed containers such as ampules, thermos-type bottles and sealed glass containers will not be able to have the pressure equalized so should not be taken into the chamber.

Food and drinks that are easily consumed and not easily spilled are preferred.

When deciding on food / drink options, remember that the time to consume them will be short.

All food, drink and medication intake should be recorded by the attendant.

Chamber Disinfection and Cleaning

It is essential that the chamber be kept meticulously free of grease, dirt, lint, dust and other combustible materials, as well as infectious materials. A suitable disinfectant should be used to clean all surfaces following each treatment day.

PPE should be worn for cleaning the chamber according to standard precautions and your facility policy.

The disinfectant should be:

- Synthetic (non-soap)
- antiseptic
- Unaffected by pressure,
- non-flammable,
- non-volatile,
- non-toxic,
- non-allergenic,
- non-corrosive,
- inert in the presence of oxygen and
- odourless (as near as possible).

Examples of commonly used chamber disinfectants are Sanizide and Simple Green d Pro 5.

Infection Control within the Recompression Chamber

Standard precautions are used, just like any other healthcare setting. Your facility's policy for handling soiled linens and disposal of infectious waste should be followed.

General guidelines for preventing cross infection:

- All patients are to use dedicated BIBS for the duration of their treatments. Cleaning of the BIBS is done when the treatment course is completed, or as needed during the treatment course.
- While testing the BIBs during the pre-treatment checks, the attendant should place their mask onto the BIBs to be used by the patient, then once tested, they should remove their mask and replace it with a clean mask for the patient to use.
- BIBs masks are washed with the selected disinfectant after each treatment. Mask straps can be washed in general purpose detergent and air dried.
- Gloves, gowns, masks and eye protection should be readily available to the attendant and used in accordance with standard precautions.
- In cases where a patient is suspected to have COVID-19, influenza, or other transmissible respiratory viruses, a higher ventilation rate may be implemented during treatment, especially during air-breaks when the patient is not exhaling into the BIBS. Other measures that may be considered include the use of surgical masks and/or rapid testing before entering the chamber.

Cleaning the Hyperbaric Chamber:

Clean the inside of the chamber with the selected disinfectant. Guidelines for choosing a suitable chamber disinfectant can be found elsewhere in this manual.

- The floor of the chamber is to be removed to access the bilge for cleaning once a month at minimum or if spills or contamination have occurred.
- At this time, all inside chamber surfaces should be cleaned and disinfected, including the hull, furniture, cushions, pillows, and medical equipment.

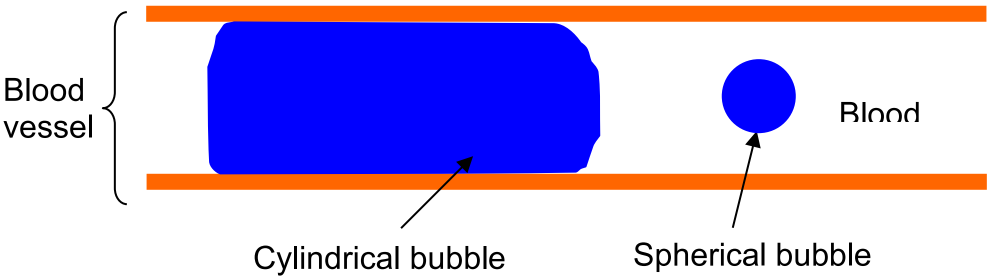
Post Treatment Cleaning of the Chamber:

- All linens, blankets, trash, urinals, bedpans and any disposable items should be removed from the chamber and disposed of per standard precautions and your facility policy.
- BIBs masks are cleaned after each use with the selected disinfectant, wiped dry and then left to air dry.
- The inside of the chamber should be wiped down after treatment with the selected disinfectant, including furniture and cushions.
- Clean linens, blankets and whatever basic supplies are deemed necessary for the next treatment should be put into the chamber.
- The chamber should always be left in a ready state in case of an emergency treatment.

Hyperbaric Oxygen Therapy for Diving Injuries

Why Provide Hyperbaric Oxygen for Diving Injuries?

1. **Reducing the bubble volume*:*** If the ambient pressure is increased, the volume of a bubble will shrink in accordance with Boyle's Law. Note that this does not necessarily mean that a blood vessel is now "opened". Remember that a bubble blocking a blood vessel may be cylindrical and not spherical!



2. **Dissolving more oxygen into the blood*:*** By increasing the partial pressure of oxygen that you are breathing, more oxygen will dissolve into the blood in accordance with Henry's Law. This means that more oxygen is available to the tissues (that had been blocked by a bubble previously).
3. **Dissolving less nitrogen into the blood:** By decreasing the partial pressure of nitrogen that the patient is breathing, less nitrogen will dissolve into the blood in accordance with Henry's Law. This means that the patient's inert gas load will decrease over time, lowering the risk of damage from inert gas bubbling. This process is known as denitrogenation.
4. **Blocking the "ischaemia-reperfusion" effect:** HBO blocks the effects of white blood cells that actually cause a lot of the damage following a gas bubble injury.
5. **Reducing swelling:** Most injuries produce swelling, which increases the pressure on the tissues locally. HBO causes vasoconstriction (closing of the blood vessels), which reduces the swelling.

How do we Provide HBO for Diving Injuries?

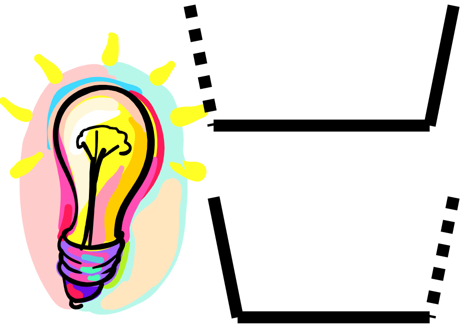
HBO is provided by means of increasing the total pressure surrounding a person. This is usually done by pressurising the chamber with AIR – unless doing deeper treatments, where other gas mixes (even containing helium) can be used. The injured diver is then given 100% oxygen to breathe while under the increased environmental pressure.

There are various ways in which the oxygen can be provided, but it firstly depends on whether the person is breathing spontaneously or not. A person that is NOT breathing cannot be treated in a hyperbaric chamber unless specific adaptations are made to the equipment, or a hyperbaric ventilator is ventilating the person. The hyperbaric ventilator is managed by a diving medical doctor that has been trained in ventilating an injured diver under hyperbaric conditions (which is not the same as in the hospital!). Note that only specific ventilators can be used in a chamber.

A Bag-Valve-Mask device dumps gas in the ambient atmosphere and will thus lead to serious oxygen build-up in the chamber. It cannot be used for ventilating an injured diver in the chamber unless a large amount of ventilation of the chamber atmosphere takes place.

The Oxygen Provision Schedule

The injured diver is put on oxygen as soon as the treatment depth has been reached. This is the start of the table. The descent time may vary – depending on whether the person is able to equalize.



A treatment table starts when at depth and ends when reaching the surface.

A diving table starts when leaving the surface and ends when the ascent starts.

All the chamber operator (and chamber attendant) has to do is follow the treatment table and provide the oxygen breathing periods and air-breaks as prescribed by the table. There are only TWO reasons why you would deviate from the table, namely:

- A diving medical doctor amends the table.
- An emergency which forces you to change the table in accordance with the EAP.

The treatment table will provide the following information:

- The treatment depth. The time you should spend at that depth.
- Which breathing gas the person should breathe (usually either 100% oxygen or air).
- The descent or ascent rate to the next depth.

Recompression Treatment

Physiology and Pathophysiology

Body Airspaces, Barotrauma and Equalization Techniques

The human body is primarily made of water and therefore incompressible. What is affected by changes in pressure are any air-filled cavities, like the middle ear, sinuses and lungs.

Ears and Sinuses

The ear is divided into three parts; the outer ear, middle ear and inner ear. The outer ear, including the ear canal, is open to the environment and therefore is not affected by pressure changes. The inner ear is completely fluid-filled and is also unaffected. The middle ear, however, is filled with air to help amplify the sound as it is transmitted from the tympanic membrane to the inner ear.

1 **Ear Barotrauma:** If the pressure inside this airspace is not continuously equalised to the ambient pressure upon descent, an ear barotrauma ("squeeze") can occur. The volume will shrink according to Boyle's Law (ref. Chapter "Physics and the Hyperbaric Environment"). This will cause the tissues to become distended and the tympanic membrane to be drawn inwards causing discomfort and pain. Blood vessels might rupture and fill the middle ear with fluids. In severe cases, the tympanic membrane also ruptures.

2 **Paranasal Sinuses:** These cavities inside the facial bone structure are also affected by changes in pressure and are susceptible to barotrauma in much the same way as

the ears. All sinuses are connected to each other through the sinus passages and to the middle ears via the Eustachian tubes and are equalised simultaneously.

3 **Sinus Barotrauma:** A sinus barotrauma on descent is relatively rare since the sinuses are connected to the ears and are equalised at the same time. On rare occasions, it can occur when the passages are blocked by mucus or inflammation. This can cause an inability to equalise the ears and sinuses. This type of barotrauma causes facial pain and can cause a rupture of the mucous membranes. Patients that suffer from a cold or allergies should not be pressurised unless in an emergency.

4 **Equalisation Techniques:** As mentioned above, to avoid any discomfort or barotrauma, the pressure in all body cavities must always be equal to the ambient pressure. This can be done in one of the following ways:

- **Swallowing**
- **The Valsalva Technique:** Blocking the nostrils and gently exhaling into the nose.
- **The Frenzel Technique:** Blocking the nostrils and swallowing at the same time**.**

It is important to equalise the ears as early and often as possible when pressurising. Should the ears not clear, the attendant needs to inform the chamber operator, who will then stop and de-pressurise a bit to relieve the pressure before attempting to clear the ears again. In case of a severe or live threatening condition, or if the patient is unresponsive, the physician can perform a myringotomy (perforating the tympanic membrane) in order to equalise the ears and sinuses.

The Lungs

Their purpose is the gas exchange. Air is inhaled and some of the oxygen be absorbed into the bloodstream through the alveoli, while carbon dioxide is absorbed into the alveoli from the blood stream. Upon exhalation, this waste product of metabolism is the released into the environment. As the lungs are also an air space within the body, they too need to be equal to ambient pressure at all times. Since both the chamber atmosphere as well as the BIBS always delivers breathing gas at ambient pressure, this is simply done by constant breathing.

Pulmonary Barotrauma: As long as the chamber occupants breathe continuously, the lungs will always equalise themselves. If the airways become blocked due to a medical condition (e.g., asthma, allergies), or by holding one's breath, the pressure inside the lungs cannot be equalised any longer and a pulmonary barotrauma can occur. A barotrauma during descent is unlikely. The main problem is during the ascent. Even a slight pressure change with blocked airways can cause lung overexpansion or even lung rupture - a pulmonary barotrauma. Symptoms and signs include:

- Dyspnoea (shortness of breath)
- Sharp, stinging pain upon inhalation, usually in one side of the chest.
- Bloody sputum
- Trachea (windpipe) distended to one side.
- Uneven rising of the chest.

Prevention: This condition can be life-threatening and is to be avoided at all costs. All occupants must be screened (stethoscope, chest x-ray) before their first chamber session. Obstructive lung diseases are a contraindication to HBO treatment unless it's a life-threatening emergency.

First Aid:
Both the chamber operator and the inside attendant must be constantly observing the occupants for any symptoms of pulmonary barotrauma, especially when depressurising. If a pulmonary barotrauma is suspected the attendant immediately informs the operator, who stops depressurising and increases pressure again until symptoms are relieved, but not more than the maximum pressure of the treatment. The attendant will assure the airways stay open and provide CPR if necessary. The attending physician will be locked into the chamber to assess the patient and perform chest drainage if necessary. Depressurisation is then resumed at the physician's orders and under his/her supervision. The patient will breathe oxygen throughout the ascent and thereafter and will be transported to the nearest ICU department for further treatment.

Decompression

The term Decompression Illness includes both Decompression sickness (DCS) and Arterial Gas Embolism (AGE).

Decompression Sickness

Also referred to as the **Bends** or **Caisson Disease**.

Caisson Disease originated from pressurized submerged chambers (caissons) used to prepare river bottoms for the placement of foundations for bridges. This condition cannot only occur in compressed air workers, in whom it was originally described, but also in commercial and recreational divers and pilots who fly at high altitudes.

After a reduction in ambient pressure, the body tissues can become supersaturated with nitrogen. This nitrogen forms bubbles due to Henrys' gas law, which then damage tissue. Today Caisson Disease is commonly called Decompression Sickness, or DCS. If sufficient amounts of nitrogen have been dissolved in tissues, and the ambient pressure decreases drastically such as with a rapid ascent, bubbles may form in those tissues and produce symptoms. Once bubbles have formed, they will increase in size as more nitrogen is diffused into them.

Arterial Gas Embolism

Also referred to as **AGE**

AGE is caused by breath holding or trapped gas in the lungs during ascent. The lungs become over-inflated and gas may be forced into the bloodstream, and eventually into the brain. Another reason for AGE can be a heart condition known as Patent Foramen Ovale (PFO), where there is a connection between the right and the left atrium, allowing venous blood-containing bubbles to enter the arterial system and the brain.

Although different in pathology, the treatment and outcome are largely the same as with DCS.

Symptoms and Diagnosis

Decompression sickness can occur after breathing compressed air in depths usually greater than 30 ft (9 m). A diagnosis of DCS is usually made by evaluating the recent dive profile, pre-dive behaviour, the exclusion of other new or pre-existing illnesses, and by performing a complete neurological and physical exam.

A number of medical conditions such as muscle and joint conditions, neck and spinal injuries, nervous system disorders, and ear and sinus barotraumas can cause symptoms that mimic DCS.

Equally important is a diagnosis of inner ear Decompression Sickness. It can have similar symptoms as middle or inner ear barotrauma but must be treated in a recompression chamber. Confusion over diagnosis can lead to a delay in treatment.

Symptom Onset

Approximately 50% of signs and symptoms will begin within the first two hours after the last dive, and 95% within the first 24 hours. Common symptoms include paralysis, weakness, vertigo, extreme fatigue, joint or muscle pain, patchy paresthesias, headache, numbness and tingling, altered skin sensation and rash.

Patient Transport

Not all hospitals have a hyperbaric chamber nearby. Over short distances, injured divers may travel by ambulance, breathing 100% oxygen, to the nearest chamber. However, for longer distances, air transport may be necessary. Planes must fly with their cabin pressure at sea level. This will prevent the bubbles in the body from expanding further. Helicopters should fly at a maximum altitude of 1000 ft (300 m) above sea level. All dive accident victims should be breathing 100% oxygen during transport.

First Aid Procedures

Any patient suspected of suffering from DCS or AGE should be started on 100% oxygen via a tight-fitting mask, preferably a non – rebreather mask or a demand valve delivery system. The increased partial pressure of oxygen in the lungs and arterial blood helps to speed up the elimination of nitrogen from body tissues and increase symptom resolution. Most divers suffering from DCI will have some level of dehydration. Intravenous fluids should be started at the earliest opportunity, which will rehydrate the patient and increase blood volume allowing oxygenated blood to reach all body tissues.

Mild cases of DCS often resolve spontaneously, or after treatment with oxygen and fluids. However, symptoms can recur, and patients may be kept under observation after oxygen is discontinued.

Treatment

Treatment for DCI includes the continuation of primary care measures as well as recompression in a hyperbaric chamber. The most commonly used treatment protocols for DCI have been determined by the US – Navy, although there are many other treatment protocols. The initial treatment usually consists of a USN TT6. This treatment utilizes 100% oxygen breathing mixed with intermittent periods of air breathing. Oxygenation is then increased nearly threefold, which allows for greatly enhanced nitrogen elimination.

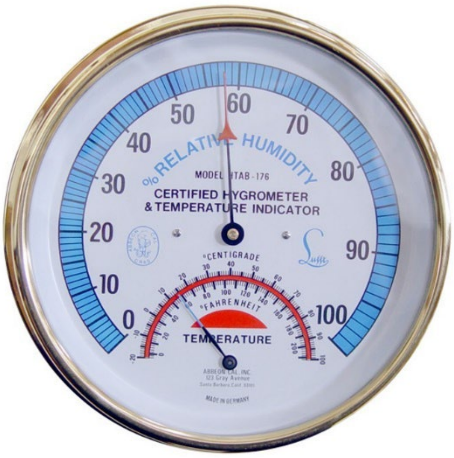
By increasing ambient pressure, existing bubbles in the tissues are reduced in size and often resolve with the first treatment. Most cases require only two to three treatments in a chamber. More resistant cases of DCI require more treatments until symptoms resolve or reach a plateau. Follow-up treatments usually require shorter tables, such as TT 5 or TT 9. Depending on the severity of the injury, hospitalization may be required to medically support the patient.

The presence of any disease, which would impair the absorption or transport of oxygen, would impair the effectiveness of treatment and recovery. Co-existing injuries, such as a pneumothorax or a near drowning episode have to be treated before a diver can be recompressed in a hyperbaric chamber.

Monitoring

Monitoring of the Chamber Environment

- **Oxygen and CO_2 Content**: The BIBS used in chambers is a “closed system” approach. You do not want any oxygen to leak into the chamber environment, as this introduces a fire risk. The chamber oxygen percentage must not be allowed to rise **above 23.5%,** which is monitored constantly by an oxygen analyzer on the control. If the oxygen content is rising and approaching the critical level, the attendant must check all breathing systems for obvious leaks, like loose connections, free flowing regulators and masks or hoods that are not sealed properly. The operator then ventilates the chamber until oxygen levels are below 23.5 % again. On rare occasions, the oxygen content can actually drop below 21%. This indicates a buildup of CO2, which is expired by the occupants as they use up the available oxygen. Some chambers have dedicated CO2 analyzers in addition to the oxygen analyzer. Regular ventilations can prevent this situation from happening, either by continuous vents or by regular high-volume flushing e.g., for 3 minutes every 20 minutes.
- **Relative Humidity:** The relative humidity inside a chamber can be a cause for concern. There can be an increased the risk of static electricity with very dry air. e.g., 20%. This situation is relatively rare since chamber occupants inside are perspiring and exhaling humidified air into the chamber environment. More common is high humidity e.g., 75%, which is uncomfortable and can increase the risk of instrument and equipment malfunction. The humidity can be controlled somewhat by regularly ventilating the chamber.



Hyperbaric Hygro- and Thermometer

- **Temperature:** When changing the pressure inside the chamber, the temperature also changes. When pressurizing it can get quite hot inside. When depressurizing, it can get cold. It is therefore prudent to have a thermometer installed, either at the panel with a sensor inside, or a hyperbaric thermometer inside the chamber, to monitor the temperature. Most modern chambers have climate control or cooling systems. Most modern chambers have climate control or cooling systems. If not, the temperature can be controlled somewhat by regularly ventilating the chamber.

Patient Monitoring

The chamber occupants are patients undergoing medical therapy for up to several hours at a time. They therefore must be constantly monitored, and treatment progress must be documented.

Minimum monitoring, in the absence of any monitoring equipment, would be frequent taking of vital signs by the attendant:

- **Pulse and respiratory rate**: If there is no timer or clock inside the chamber, have the operator time it on the outside and tell the attendant (e.g., “Stand by, START...stand by, STOP”)
- **Blood Pressure:** Only manual sphygmomanometers are admissible into the chamber, No electronic devices, devices containing mercury or that use glass tubes. When not in use, the release valve must stay open. Since a sphygmomanometer measures blood pressure in mmHg above ambient pressure, the readings are not affected by treatment depth. However, while pressure changes are occurring, accurate readings are not possible since the cuff’s volume will change along with the pressure.
- **Electrocardiogram (ECG):**

There are ECG units that are specifically designed for use inside a hyperbaric chamber. However, all their system components must be constructed to withstand the pressure as well as conform with the safety regulations regarding electrical equipment in high oxygen environments. They are therefore prohibitively expensive and not common. A standard ECG monitor can be used on the outside, with the leads being fed into the chamber through cable penetrators.

Choosing the Oxygen Dosage

The correct “dose” of oxygen for the initial treatment of DCI is accepted worldwide as the USN TT6 or equivalent.

The doctor will almost always use the USN TT6 or equivalent, unless there is a good reason to use another treatment table.

There are some reasons that a USN TT5 or equivalent might be ordered, rather than a USN TT6:

- Missed decompression stops of a diver with no symptoms or signs of DCI, as a preventive measure.
- The treatment of a symptom-free buddy of a diver with DCI, as a preventative measure. In practice the buddy usually does the USN TT6 with the injured diver if funds allow.
- Type 1 or pain-only DCS. It must fully respond to therapy within the first ten minutes of pressure. If not, the treatment table is extended to a USN TT6.

US Navy TT6A. This table is rarely used anymore, and only under special circumstances:

- Confirmed Gas Embolism
- Recompression to 50 MSW will take place within 10-15 minutes.
- You have adequate backup to extend the treatment if you overstay the bottom time of due to complications (e.g., return of symptoms or pneumothorax)
- Chamber facilities able to handle this treatment table.
- Personnel trained in the use of the treatment table.

Comex-30 table. Also rarely used anymore and only under special circumstances:

- Severe cases of DCI that deteriorate in spite of treatment.
- Chamber capabilities - depth of 100 fsw/ 30m.
- Mixed gas capability (50/50 heliox or nitrox) available.
- Adequate protection for the attendants.

Personnel must be fully- trained in the use of the treatment table offered at the recompression facility.

Treatment Tables

General Considerations

When performing diver recompression or hyperbaric oxygen treatment, specific treatment protocols are followed, called recompression or treatment tables. These tables are a detailed schedule of a treatment. They specify the duration of the treatment, treatment pressure (depth) treatment gas, and descent and ascent rates.
There are many diver treatment tables in use throughout the world. The US Navy, Royal Navy and Comex tables are the most commonly used.
There are two different types of tables:

Air (or mixed gas) tables: Mainly used in commercial diving to decompress deep- and saturation divers. Can be up to 72 hrs long.

Oxygen treatment tables: The occupants are breathing 100% oxygen during most of the treatment. This allows for greatly reduced treatment times. Oxygen speeds up off-gassing of excess nitrogen. Oxygen also reduces inflammation and accelerates the regeneration of damaged tissues. For that reason, oxygen tables are also used in treating non-diving related injuries like carbon monoxide poisoning and gas gangrene. A typical oxygen treatment table is 2 - 5 hours long.

The most commonly used tables are the ones developed by the US Navy in the sixties and seventies, USN TT6, 5, 9, and 6A.

US Navy Treatment Table 6

This is the ¨workhorse¨ of treatment tables. It consists of three oxygen periods of 20 minute at 60 fsw (18 msw), interrupted by three 5-minute air breaks. An ascent to 30 fsw (9 msw) is then executed, with the patient breathing oxygen. At 30 fsw (9 msw), there are two 60 minute oxygen periods and two 15-minute air-breaks, before ascending to the surface while breathing oxygen.

It can be used for almost any type of decompression injury. If in doubt, recompress on a USN TT6.

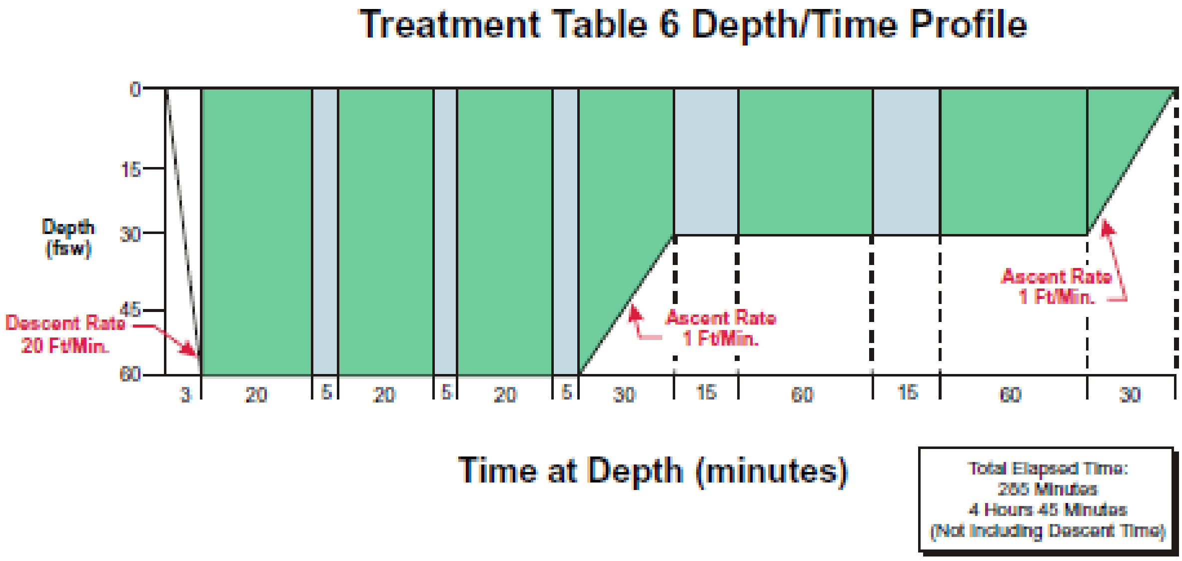
The USN TT6 is mainly used for:

- DCS type II
- Arterial Gas Embolism
- DCS type I if there is no complete relief after the first 10 minutes at 60 fsw (18m fsw)
- When there was no neurological exam before the start of the treatment
- Severe carbon monoxide poisoning, smoke inhalation or cyanide poisoning
- Asymptomatic divers with omitted decompression longer than 30 minutes.
- Treatment of unresolved symptoms following a previous treatment.
- Recurrence of symptoms shallower than 60 fsw (18m msw)

General rules:

- Descent rate is 20 fsw (6 msw) per minute, or as fast as occupants can equalise comfortably.
- Maximum ascent rate 0.3m/1ft per minute. When ascending too fast, stop the ascent and let time catch up.
- Time on oxygen begins on arrival at treatment depth.

- If oxygen breathing must be interrupted due to oxygen toxicity, allow a minimum of 15 minutes after the seizure has completely subsided, then resume schedule at the point of interruption.
- Table 6 can be extended by two 20-minute oxygen/5-minute air periods at 60 fsw (18msw) and up to two 60-minute oxygen/15-minute air periods at 30 fsw (9 msw).
- Attendant breathes 100% oxygen during the last 30minutes at 30 fsw (9 msw) and during ascent to the surface if there was not more than one extension. With more than one extension, the oxygen breathing period at 30 fsw (9 msw) is increased to 60 minutes. If the attendant had been diving in the past 12 hrs, this period is increased by an additional 60 minutes.



US Navy Treatment Table 5

This table is basically a shorter version of the USN TT6. It specifies only two oxygen periods of 20 minutes and one 5 minute air-break at 60 fsw (18 msw), and one 20-minute oxygen period plus two 5-minute air-breaks at 30 fsw (9 msw).

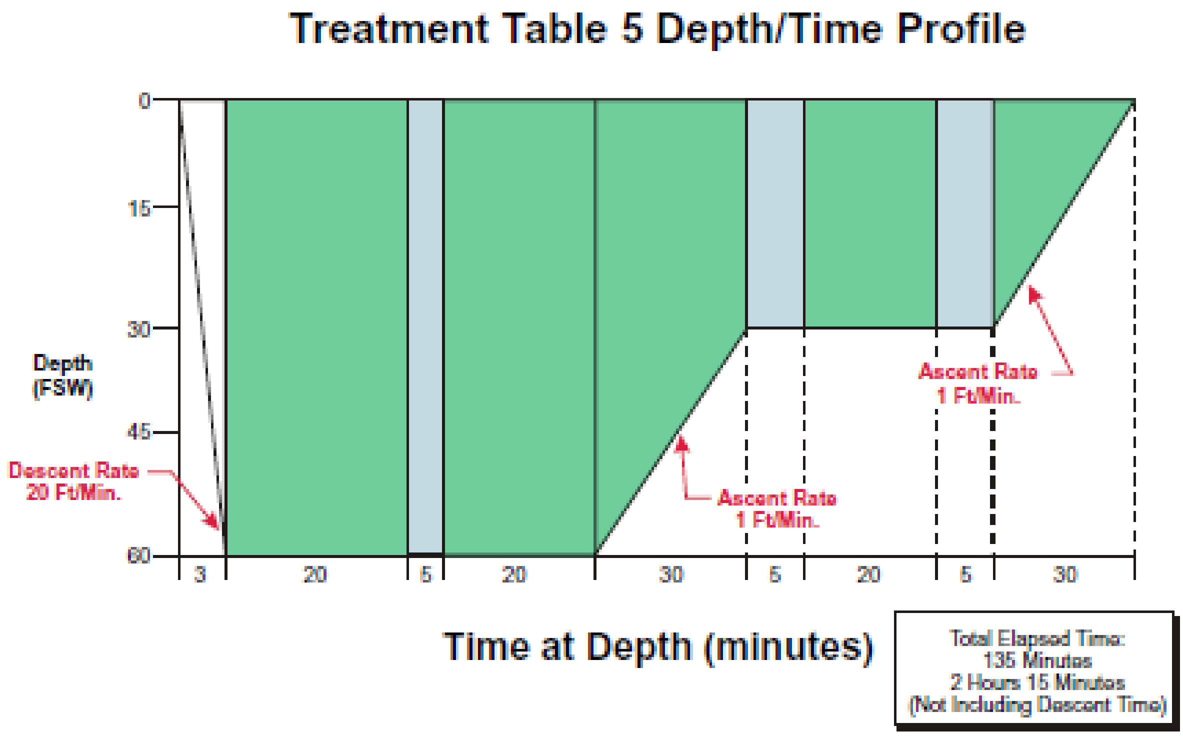
It is mainly used for:

- DCS Type I when neurological signs/symptoms have been ruled out.
- Follow up treatments for residual signs/symptoms.
- Omitted decompression of less than 30 minutes and asymptomatic.
- Carbon monoxide poisoning
- Gas gangrene
- Divers that exceeded surface intervals on sur-d–dives and are asymptomatic.

General Rules:

- Descent rate 20 fsw (6 msw) per minute or as fast as occupants can equalise comfortably.
- Ascent rate not to exceed 1 fsw (0.3 msw) per minute
- First oxygen period begins on arrival at treatment depth.
- If oxygen breathing must be interrupted because of oxygen toxicity, allow a minimum of 15min off oxygen before continuing at the point of interruption.
- This treatment table may be extended by up to two oxygen periods with no air-breaks at 30 ft (9m).

- If a neuro exam at depth reveals any neurological symptoms, the treatment is to be converted to a USN TT6.
- The attendant breaths 100% oxygen during ascent from 30 ft (9m) to the surface. If the attendant had been diving in the previous 12 hours, this period is extended by 20 minutes at 30 ft (9m).



US Navy Treatment Table 9

This is a classical hyperbaric oxygen (HBO) treatment table. It is primarily used when treating non-diving related injuries. This table is shallower than recompression tables but has longer oxygen periods.

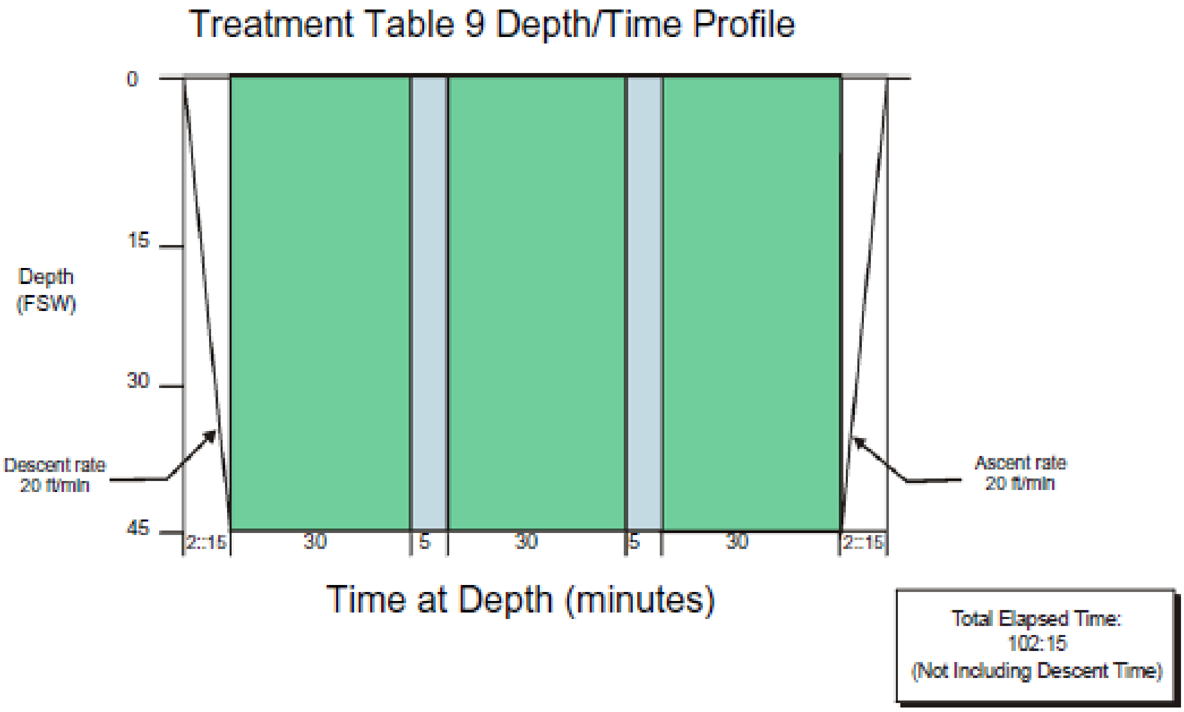
It is mainly used for:

- Hyperbaric wound care after major surgery (e.g., skin grafts).
- Carbon monoxide or cyanide poisoning.
- Smoke inhalation.
- Treating residual signs/symptoms of DCS or AGE

General Rules:

- Descent rate 20 fsw (6 msw) per minute, or as fast as occupants can equalise comfortably.
- 20 fsw (6 msw) per minute in HBO treatment, as slow as 1 fsw (0.3 msw) per minute in diver treatment as directed by the Physician.
- Oxygen treatment begins on arrival at treatment depth.
- If oxygen treatment must be interrupted because of oxygen toxicity, oxygen breathing may resume 15 minutes after symptoms have subsided. The schedule is then resumed at the point of interruption.
- If the patient cannot tolerate oxygen at 45 fsw (15 msw) the doctor can modify the treatment depth to 30 fsw (9 msw).

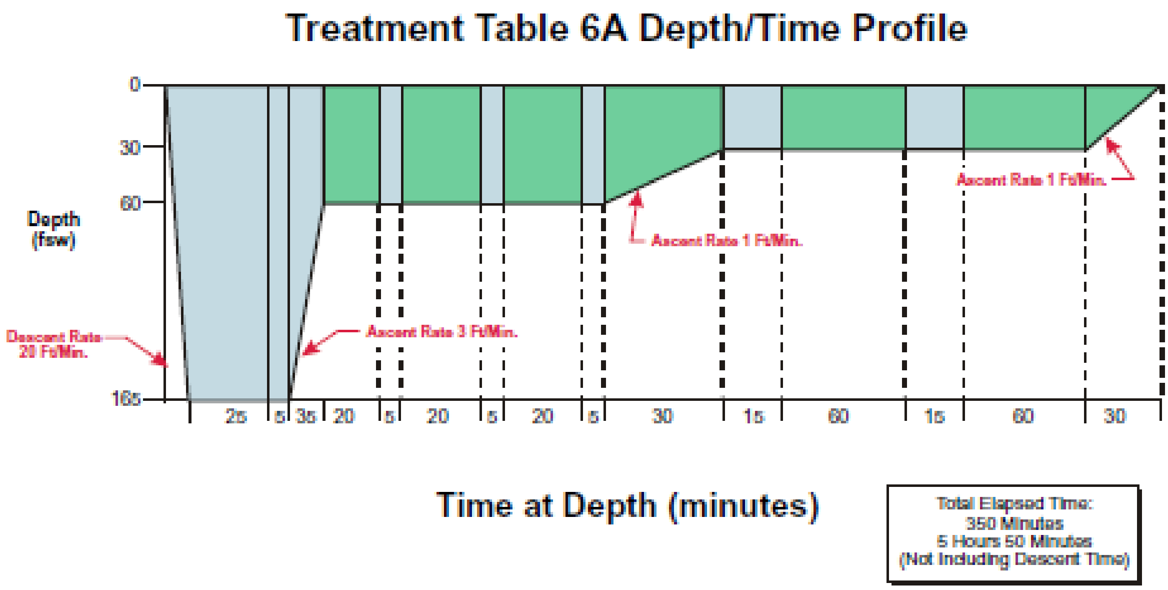
The attendant breaths 100% oxygen during the last 15 minutes at depth and during the ascent to the surface.



US Navy Treatment Table 6 A

This is a USN TT6 with a 30-minute excursion to 165 fsw (50msw) on mixed gas (50/50 heliox or 50/50 nitrox). It is only used in very severe cases of AGE or DCS. It requires a chamber with advanced life support equipment and mixed gas capabilities. It further puts the attendant at risk of getting nitrogen narcosis and therefore being unable to assist the patient. This table is rarely used anymore.

For more information on this and other specialized tables, consult Volume Five of the US – Navy Dive Manual.



Chamber Maintenance

General Considerations

Inadequate and/or incomplete maintenance of a recompression chamber facility can result in deterioration below a level of optimal safety and readiness and/or failure of systems to a degree that could affect operational safety.

Regular Testing and Calibration of Equipment

Inadequate maintenance of oxygen handling equipment, chamber controls, and safety equipment can result in equipment failure, representing risks for both operators and occupants. For example, uncalibrated depth gauges can interfere with approved dive tables, exposing the patient and tender to unknown partial pressures of oxygen and inert gases.

The safety officer should be responsible for ensuring that all equipment is regularly checked and serviced. Pressure-relief valves, gauges, and analyzers should be regularly calibrated.

Documentation of calibrations and servicing should be made available to chamber staff if requested.

Labeling of Gas Outlets

Inadequate labeling of oxygen system components, especially inlets & outlets, risks them not being utilized properly during treatments or identified during emergencies. All essential controls on an oxygen system, especially gas outlets, should be clearly labeled. This applies to all gas mixtures. If any chamber employee notices inadequately labeled oxygen system components, the safety officer should be notified immediately.

Note: it is paramount that the gases delivered at every labeled outlet are checked prior to their first use by reviewing the attached certificate(s) of analysis or, preferably, by continuous gas analysis.

Lubricants

Many common and accepted lubricants and consumable materials are not safe for use within a hyperbaric environment, especially in the presence of high concentrations of oxygen.

The criteria by which materials are judged to be safe for use in a hyperbaric environment should include the following:

- Suitably pressure-rated and oxygen-compatible
- Nonreactive with system elastomers and other similar materials
- Nontoxic
- Noncorrosive

Materials should be clearly identified for their intended use and should be packaged to keep out contaminants. Lubricants should be used sparingly and should not be used to correct equipment flaws (e.g., on non-sealing joining surfaces or to compensate for a poor fit). Fluid levels should be checked before a treatment and excess lubricant should be removed prior to use of the equipment. Lubricants should be replaced at specified intervals set by the manufacturer.

Electrical Safeguards

Any electrical faults or failures of a chamber's protective equipment present a considerable risk to the safety of the operating environment. All electrical circuits, ground fault interrupters (GFIs), and line insulation monitors (LIMs) should be tested before each treatment session to ensure that they are functioning normally and that no live conductors are grounded.

A failure to de-energize electrical equipment during a fire, especially in facilities with a sprinkler or deluge system, can be exceedingly dangerous, due to the risk of electrical shock and even death if water comes in contact with an electrical fire. Any electrical equipment in a recompression chamber facility that is not life-critical should be de-energized prior to the activation of a sprinkler or deluge system (unless it is adequately waterproofed).

Cleaning of Filters

Blocked or partially blocked filters reduce the efficiency of chamber operations, provide a risk where rapid decompression may be required, and if filters fail as a result of excessive loading, may introduce dirt and contaminants into the chamber environment. If the contaminants include flammable materials (such as volatile organic compounds), the risk of a chamber fire increases dramatically.

The chamber gas supply inlet filters should be cleaned or changed at least annually. Inlet filters for regulators, flow controls, and the exhaust system also require annual maintenance. Refer to the manufacturer’s recommendations before conducting any maintenance or repairs.

Systems Cleaning Procedures

Ineffective or incomplete cleaning of hyperbaric piping and gas storage systems can introduce dangerous substances into the systems, posing a risk of fire or toxic contamination.

- After initial installation, repairs, or modifications of any gas supply or control system, a cleanliness certificate should be issued that meets the satisfaction of the safety officer.
- Suitable cleaning procedures should be documented and certified as effective by the safety officer prior to being implemented. These procedures should preferably include objective inspection and testing instructions.

Replacement Parts

The use of nonstandard spares and replacement parts can result in premature equipment failure. The safety officer should be responsible for ensuring that only manufacturer-authorized components are used during both initial installation and subsequent maintenance of all equipment.

Authorized Work

All installation, repair, and modification work to hyperbaric chambers and their associated equipment directly affect the safe function of the units. The safety officer should ensure that only competent personnel perform repair and maintenance work and that all such work is performed according to the provisions of both legal requirements and the equipment manufacturers’ manuals. All equipment should then be fully tested, and the results logged after any repair or maintenance work is performed.

Maintenance Logs

A lack of operating and/or maintenance logs precludes adequate control of maintenance procedures, potentially resulting in premature equipment failure. The safety officer should sign off on all maintenance procedures and ensure that logs of all operating and maintenance procedures are maintained. These logs should be made available to any chamber personnel or government inspectors if needed.

Additional Elements

Adequate and effective systems maintenance requires that the following additional elements be addressed:

- oxygen piping systems should be checked monthly for leaks (especially if oxygen monitors in the chamber facility are regularly obtaining values higher than 21.0%)
- Gas flows should remain unobstructed
- gas supplies should be analyzed semi-annually
- All automatic drains should be checked (to ensure no condensate is discharged, drain valves have no blockages, and filter elements are not saturated)
- Safety systems should be activated correctly and efficiently (e.g., deluge system, electrical alarms, emergency power system, backup gas supplies, etc.).

Physics of the Hyperbaric Environment

This chapter describes the basic physical principles of diving and hyperbaric exposures. A thorough understanding of those principles is essential to safely operate and maintain a hyperbaric chamber and to effectively tend to its occupants.

Gases Used in Diving & Hyperbaric Systems

Various gases are used in sport diving and hyperbaric therapy, the most common being compressed air. However, with the increasing popularity of extreme, or technical diving, we will encounter mixes of different breathing gases. This section describes the most often used gases.

Air (N_2, O_2):

The most popular gas mix used in diving due to its simplicity in storage and application. It contains approximately. 21% oxygen and 79% nitrogen, with very small amounts of other gases: argon (Ar), CO_2,helium (He), H_2O and other more exotic gases such as neon (Ne).

Oxygen (O_2):

This the only gas actually consumed by the human body. Without O_2 we are not able to survive. However, when excessive amounts of it are breathed under pressure it can be extremely poisonous (oxygen toxicity). 100% O_2 is also extremely hazardous when added to any combustion process. Fires in and around chambers are the reason for most of the fatalities in hyperbaric facilities.

Nitrogen (N_2):

Accounts for 79% of the air we breathe. It is colourless, odourless and physiologically inert. That means our body has no use for nitrogen. However, at pressure, and like all other gases, nitrogen is absorbed by the blood. If not allowed to be released slowly, it results in DCI. If it is breathed at an increased pressure, it can also have a narcotic effect. This so called ¨ nitrogen narcosis ¨ is characterised by euphoria, decreasing motor skills and poor judgment.

Helium (He):

Like nitrogen, it is colourless, odourless and physiologically inert. Helium is a rare gas in our atmosphere, and expensive to produce. Since it doesn’t have the narcotic effect of nitrogen, it is used as a replacement for in deeper diving. A major disadvantage is its high heat conductivity, which can cause severe decrease in body temperature (hypothermia) in divers or chamber occupants breathing a helium mix. A somewhat humorous side effect is the temporary distortion of speech resulting in chamber occupants talking in a ¨ Donald Duck ¨ type voice, making communication difficult.

Carbon Dioxide (CO_2):

Carbon dioxide is a waste product of the metabolic process of the human body. The respiratory process expels it. It is colourless, odourless and tasteless. CO_2 in itself is not poisonous, however since it replaces the O_2 in a breathing gas, it can be harmful when breathed in higher concentrations. Like nitrogen it can cause narcosis and interferes with the acidity level of the blood. We must therefore always be aware of the CO_2 content of our chamber and keep it down by regular ventilation or scrubbing the chamber environment.

Pressure

Pressure is defined as the force acting on a certain area:

Pressure = Force ÷ Area (P = F/A)

Using imperial units: pressure (psi) = force (pounds or lbs) ÷ area (ft^2).

Using metric units: pressure (pascals or Pa) = force (Newtons or N) ÷ area (m^2).

The metric term for force (N) is determined by mass (in kg) multiplied by the gravitational constant, g (in m/s^2).

In diving and hyperbaric treatments, the units for pressure are usually expressed as absolute atmospheres (ATA), atmospheres (atm), bar (kg/cm_2), pounds per square inch (psi), feet or meters of sea water (fsw or msw), or inches mercury (inHg) or mm mercury (mmHg).

We distinguish different types of pressure as follows:

Absolute Pressure:

Absolute or total pressure is the sum of the atmospheric pressure and any additional pressure acting on a body – for example, hydrostatic pressure is the sum of atmospheric pressure and depth; gas pressure is the sum of atmospheric pressure and compressed gas.

The pressure is expressed in atmospheres absolute (ATA), psi_a or bar_a, with $_a$ denoting the term absolute.

1 ATA is the absolute air pressure at sea level: 14.7 psi(a), 1 bar_a, 760 mmHg, or 29.92 inHg. It results from the total weight of the atmosphere on any object.

Atmospheric Pressure:

Atmospheric pressure is only the additional weight of an fluid (air/gas or water) acting on a surface.

The terms atm, psi_g or bar_g are used to denote pressure above the baseline of sea level, or 0 atm. This correlates to 0 fsw or 0 msw.

Note that for all calculations relating to the ideal gas law, absolute pressures are used, in ATA.

Hydrostatic Pressure:

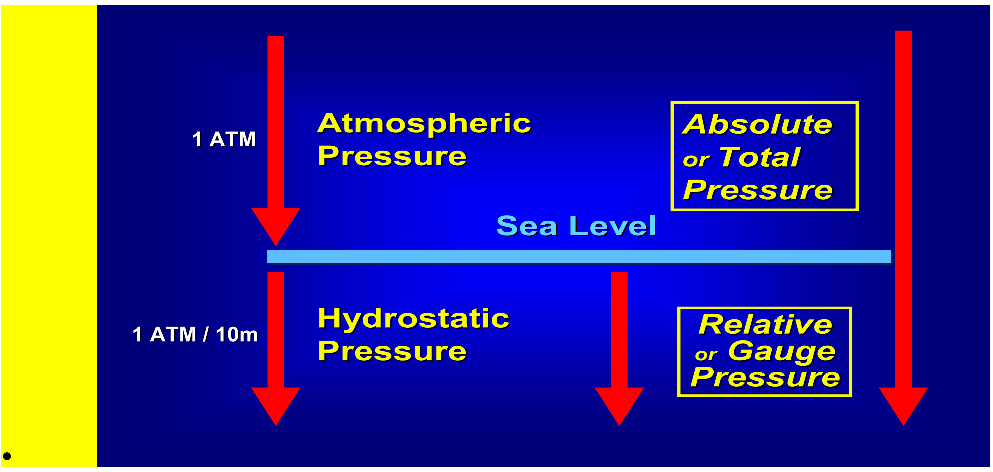
Hydrostatic, or water pressure, is exerted by the physical weight of the water. It acts on all bodies immersed in it, at all angles, and increases with depth.

33 fsw or 10 msw exerts 14.7 psi or 1 bar pressure above the weight of the atmosphere at sea level.

Note that in fresh water, the values would be 34 fsw or 10 msw.

Gauge Pressure:

Gauge pressure is the pressure in an environment without regard to absolute pressure. All gauge units are zero at sea level.



Partial Pressure:

Partial pressure is the pressure of an individual gas in a gas-mix. It is directly proportional to the percentage of that gas in the mixture.

In normal air, with almost 21% oxygen and almost 79% nitrogen, the relevant partial pressures are ±0.21 ATA for oxygen (ppO_2) and ±0.79 ATA for nitrogen (ppN_2).

Gas Laws and their Effects

All gases are affected by three factors: volume, pressure and temperature.

The different gas laws explain the relationships between these factors.

There are 5 gas laws, all derived from the ideal gas law, a formula based on a hypothetical gas which behaves ideally under different conditions.

$PV = nRT$ where

P is absolute pressure, in N/m_2 or psi

V is volume in m^3 or ft^3

n is the number of moles of gas present (and is specific to the type of gas).

R is the universal gas constant: 8.3145 (metric) or 1545.4 (imperial)

T is absolute temperature: Kelvin (K) = °C + 273.15, and Rankine (R) = °F + 459.67

For diving and hyperbaric practices, the following laws have relevance:

Boyle's Law

Henry's Law

Charles' Law

Guy-Lussac's Law, and

Dalton's Law

Boyle's Law:

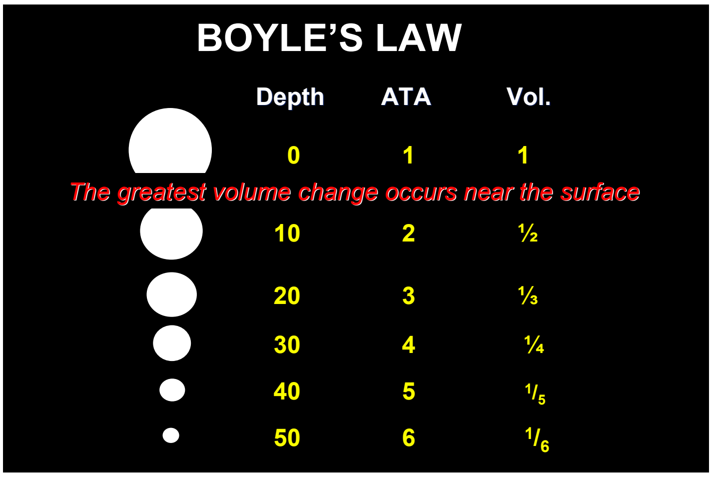
This is the most important law in diving and hyperbaric science.

Simply put, it states that at constant temperature, the volume of a gas varies inversely with absolute pressure, whereas density varies directly with absolute pressure.

$P_1V_1 = P_2V_2$

This means, that if we take a collapsible airspace (e.g., a balloon) on a dive, its volume will decrease upon descent. Since there is still the same amount of air in that balloon, this air will be compressed, and its density will increase.

All this will happen in the same ratio to the increasing depth.

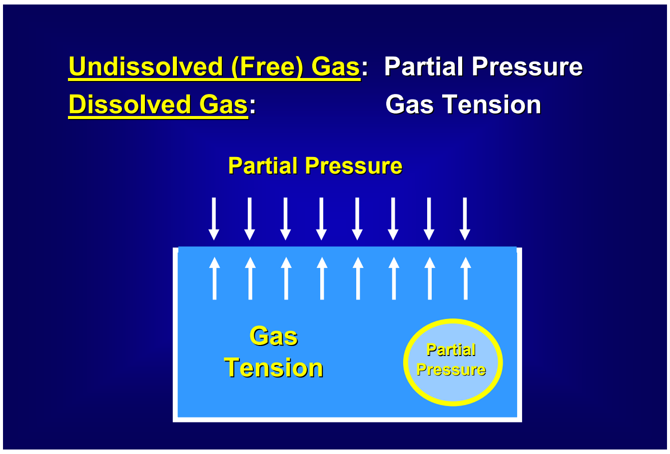


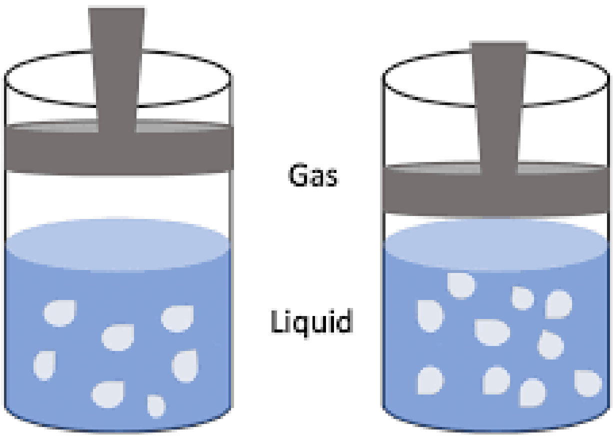
The opposite will happen if we inflate a balloon at depth and then bring it to the surface. The volume will increase, and the density of the air inside decreases at the same ratio as the decreasing depth.

Our primary concern here is barotrauma.

Henry's Law:

Simply put, Henry's law states that the amount of a gas dissolved in a liquid at a given temperature is a function of the partial pressure of that gas and the solubility coefficient of the gas in that particular liquid





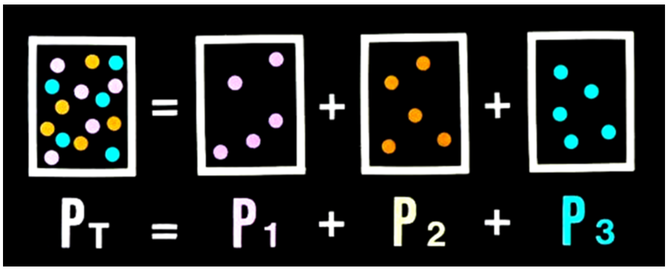
This means that a certain amount of gas can be dissolved in a liquid, if this liquid is under pressure. The higher the pressure, the more gas can be dissolved. If that pressure drops, the gas is released again in form of bubbles.

This is the principle behind oxygen and nitrogen dissolving and then being released when diving or being pressurized and then depressurized in a hyperbaric chamber.

Dalton's Law:

Also known as Dalton's Law of partial pressure, it states that, in a gas mix, the total pressure of gases is equal to the sum of the partial pressures that would be exerted by each of the gases if each gas alone were present and occupied the total volume.

$P_{total} = p_1 + p_2 + p_3 + ...$

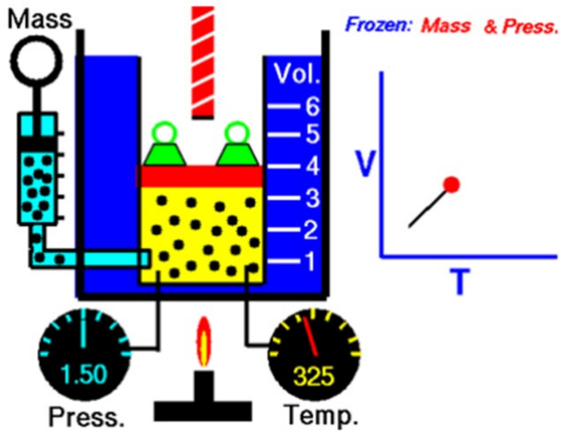


Charles's Law:

It states, that at a constant pressure, the volume of a gas varies directly with absolute temperature. However, given that volume is constant in a standard chamber environment, temperature changes will result in changes in pressure, rather than volume.

$V_1/T_1 = V_2/T_2$

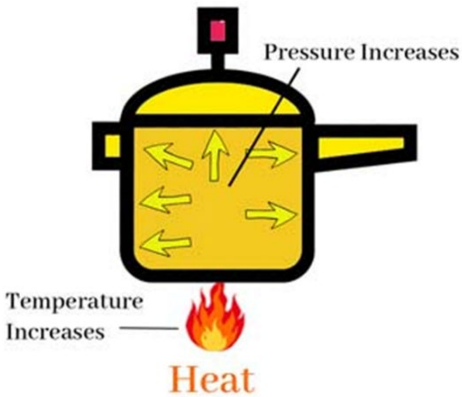
A gas will expand when heated, and where pressure is maintained at a constant value.



Gay-Lussac's Law:

This law states that at a constant volume, the pressure of a gas is directly proportional to the temperature of the gas. This implies that if the temperature is doubled, the pressure is also doubled.

$P_1/T_1 = P_2/T_2$



This means as the pressure changes, so does the temperature. A scuba cylinder or a hyperbaric chamber gets hot when compressed, and cold when the pressure is released.

Note that this occurs at constant volume only and should not be confused with adiabatic heating or cooling (see further down).

Other Effects of Gases under Pressure

There are two dynamic processes that occur as pressure changes and the actual amount of gas changes. These will be observed in hyperbaric operations, and are discussed due to the potential dangerous impacts they can have.

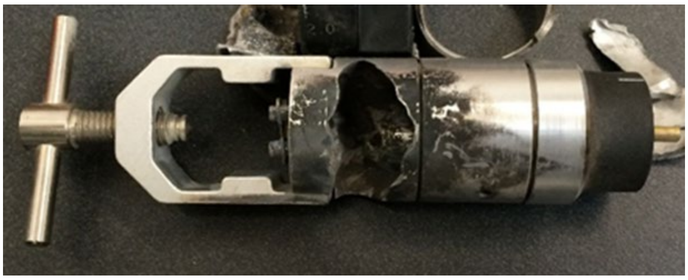
Note that is not the physical volume or a container that is applicable (i.e., the cylinder or hyperbaric chamber), but the volume determined by the partial pressure (the actual number of molecules). So, not the amount of space but the actual amount of gas.

Adiabatic heating or cooling

Also known as the heat of compression, gases will heat rapidly where pressures increase rapidly, and may lead to ignition of a material in a volatile state.

For example, where oxygen is flowing in a pipe at 2,000 psi (137 bar) and flow abruptly ceases, the resultant spike in pressure can result in temperatures as high as 1,900 °F (±1040°C).

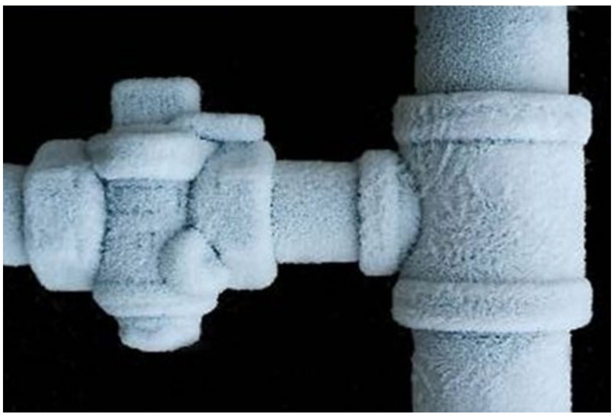
Simply put, the energy contained in the mass of the gas traveling at a speed is converted into heat when abruptly stopped. We never use a ball valve or quick acting valve in an oxygen system at pressures above 125 psi (8.6 bar). Our primary concern is fire safety.



Similarly, if something is placed in the medical lock, and pressured rapidly, it will heat rapidly. One must take care not to burn someone when the item is taken into the chamber from the lock.

Adiabatic cooling is not likely to have any major impact safety, although rapid decompression from 3 ATA will result in a cool environment inside the chamber. In general, chamber exhaust systems are not capable of decompressing a chamber rapidly enough to cause harm.

The Joule Thompson effect



The most common experience of rapid cooling due to the Joule Thompson effect can be seen on high pressure regulators in humid environments. As gas passes through an orifice, it cools rapidly. Moisture in the surround air cools and then freezes on the outside of the regulator.

This is also how refrigerators work, and this effect is used in refrigerant coolers in compressed air systems, to remove moisture.

The important lesson here to know is that if the high pressure compressed gas is moist enough (where the filters are not working effectively), it is possible to freeze the moisture inside regulator, and prevent it from operating correctly – it usually shuts off all flow but can result in free flowing (causing over-pressure downstream).

The lesson here is to ensure proper maintenance of air quality.