

Neptuno's World Articles

The scariest Techdiver thought, undetected contamination in the gas we breathe.

A MUST READ for all divers, dive shops and fill stations, your life can depend on it.

A short introduction:

This is an article extracted from [The Deco Stop](#) posted by *swampdiver*, a medical doctor, after some research about a recent incident which occurred to Michael Barnette in June 2004 during a shallow cave dive with Nitrox 32, where he experienced several acute medical symptoms so bad that he almost had to be rescued by his dive buddies.

After the dive he reported a smell in his tanks gas resembling synthetic oil and sent a gas sample to a recognized breathing gas laboratory. The analysis came back reporting that the AIR (yes JUST AIR!!! they said!!!) was good and compliant with the CGA Grade E standard. Not happy with the weird and suspicious results he sent it to a better lab where they conducted further tests and found traces of TOLUENE!!!! in the nitrox mix, apparently from a compressor that overheated resulting in the break down of the synthetic oil. TOLUENE is one of the gases produced from that break down.

BIG recommendation, ALWAYS SNIFF YOUR GAS BEFORE YOU BREATHE IT !!!

Here this very good article:

TOLUENE INCIDENT ANALYSIS/DISCUSSION

After spending the last month or so speaking with various physicians, breathing air lab directors, a carbon supplier, a filter manufacturer, a couple certified Bauer compressor technicians, a compressor oil manufacturer, and several people with experience in the field of thermal and oxidative degradation of oils, I have concluded this toluene episode likely has quite significant ramifications for the dive industry which need to be further explored and researched. After speaking with many of the experts noted above, it appears this incident is not a 'one-off' external-source toluene contamination incident, but likely represents a systemic industry wide problem that presents sporadically only when certain climatic, compressor, oil, and filtration conditions are met. What is worrisome about this incident is the potential frequency with which these conditions likely do occur during the production of compressed breathing gas particularly in the commercial realm, and the subsequent risk of serious diver injury and/or death. The technical diver will always be at the greatest risk from exposure to a volatile vapor contaminant, and as one toxicologist said after reviewing this case, "the technical diver may be the ultimate canary in a coal mine" due to the high partial pressure exposures at depth to these breathing gas contaminants.

I thought it beneficial to present the knowledge I have gleaned from my own reading and experience around this interesting case of a non fatal toluene poisoning as well as pass on what advice the above experts have offered. It is hoped that by presenting these issues here on TDS to a well informed global technical dive community that some of the concerns, and possible remedies might then also filter down to the rest of the dive industry and community so as to prevent future similar episodes. Knowledge and safety through education as the saying goes.

This is meant to be an educational discussion and not blame a particular business as many of these issues discussed will be relevant to most fill stations. It is apparent that many of the technical issues and risks illustrated by this case have either been poorly understood to date within the dive industry, have not been researched adequately, or may not have been advertised adequately by those involved in the compressed breathing gas industry who have understood these risks.

It does appear though that there are certain high risk geographic areas for these problems and Florida because of its climate, particularly

at the time of year this incident occurred, is one of them. Although Florida is used as an example for incident analysis purposes, other geographic areas with sustained periods of high temperature and humidity would also potentially see higher rates of these contamination incidents.

As there is a fair amount of information to digest I thought it might be best to break it into sections as follows:

- 1) Incident data and toluene toxicology
- 2) Toluene production from thermal (pyrolytic) and oxidative degradation of compressor lubrication oils: how?
- 3) Toluene filtration breakthrough: how did it happen?
- 4) Determining Desiccant Saturation Status
- 5) Prevention of future incidents and how to assess a fill station's potential gas contaminant risk
- 6) Future research needed

Prior to proceeding if one is unfamiliar with compressor and filtration design, theory, operation, and maintenance then Ted Green's article is the best source of information I have seen to date on many of these topics. You can find bits and pieces elsewhere, but this is the first time I have seen this information posted all in one place. Please note Ted's important continued emphasis on keeping the compressor cool, clean, and the filtration dry at all times as this is the key to the minimization of the risk factors described in this incident. Heat should become a four-letter word in terms of breathing gas production and hopefully at the end of this discussion it will be clear or somewhat clearer as to why.

[Understanding SCUBA Compressors and Filtration by Ted Green](#)

1) Incident discussion and toluene toxicity

The second breathing gas analysis revealed Barney's tank was contaminated with toluene, a volatile aromatic hydrocarbon similar in structure to benzene. When one reviews the literature on toluene toxicology there was significant research done on animal and human exposures at 1 atm during the 1970's and 1980's, but very little research has been done since this time period despite the 1980's literature saying further research into low level exposure was badly needed. There are no previous cases of divers exposed to toluene that I could find, and for obvious reasons no research on hyperbaric toluene exposure has been done. Most of the data on acute exposure comes from adolescents who 'sniff' or 'huff' toluene containing substances such as spray paint, glue, or gasoline (7 percent toluene by weight) in order to experience a rapid high or euphoria.

In this particular case it is informative to list the symptoms experienced by Barney and ask the question is toluene responsible for the diver's symptoms? I will group them into central nervous system (CNS) and gastrointestinal (GI) complaints.

CNS Symptoms

- taste alteration described as "rubbery taste"
- feeling odd
- dream-like state
- distinct gaps in memory
- impaired vision and depth perception
- mental capabilities severely impacted with inability to discern direction of arrows in cave
- confused as to time and place with inability to recall buddy's name
- no anxiety or panic
- headache

GI Symptoms

- mild nausea

Assessment by Barney post dive: "that was not cool!"

Other important details of note: diver 30 something years old, Nitrox 32 percent, initially diver "blitzed at a rapid pace" according to buddy, maximum depth 80 ffw (3.5 atm), 30 minute run time, symptoms resolved quickly on surfacing and with breathing 100 percent O2 at deco stop for 5 minutes.

Toluene exposure can result from inhalation of the vapor, and ingestion or skin contact with liquid toluene, a clear colorless volatile liquid at room temperature. The inhalational route leads to rapid systemic absorption (just like an anesthetic) with blood toluene levels rising within ten seconds, and peak blood levels reached about 15 to 30 minutes after exposure. Toluene and most volatile organic solvents are highly fat soluble and hence enter the tissues with the highest blood flow such as the brain, kidney, and liver quickly. Its toxic effects following inhalation appear rapidly in the CNS and may be enhanced by age, liver disease, previous acetaminophen (Tylenol) or aspirin ingestion as these drugs are metabolized by the similar pathways in the liver. Eighty percent of toluene is metabolized by the liver and the final metabolite is excreted in the urine. Twenty percent of toluene is eliminated via the lungs unchanged, and is why one can often smell toluene on the breath of individuals exposed to the vapor.

Toluene odor is easily detected by the human nose, and depending on what source one quotes, the odor threshold is 80 ppb, however to actually recognize the vapor as toluene and not just a generic volatile organic compound (VOC), a level of up to 8 ppm is quoted. These odor concentrations are all well below the levels one might see any of the short term adverse effects at 1 atm. In any case, most noses should be able to pick up very low concentrations of toluene in the breathing gas well below what the concentrations the lab will be looking for. The literature does report that some individuals do have better sensitivity than others for detecting toluene using smell.

The CNS effects described for acute toluene exposures are very similar to what Barney experienced as listed above. The experience is similar to acute alcohol intoxication and several papers describe exposing workers to alcohol to assess their potential occupational toluene sensitivity. Like many CNS depressants toluene may initially cause a state of euphoria with giddiness, but as the concentration increases CNS depression and narcosis ensues. Physiological effects will depend on the partial pressure at depth and duration of exposure. Numerous signs and symptoms of CNS dysfunction are described in the literature including dizziness, disinhibition, confusion, hallucinations, amnesia, bad taste, impaired coordination, tinnitus (ringing in ears), decreased manual dexterity, decreased color discrimination and accuracy in visual perception, fatigue, and at higher doses tremors, seizures, paralysis, coma, and death. In one reference from the DOT looking at toluene exposure (abuse and occupational) and driving risk they concluded "acute and chronic exposure to toluene can result in severe impairment."

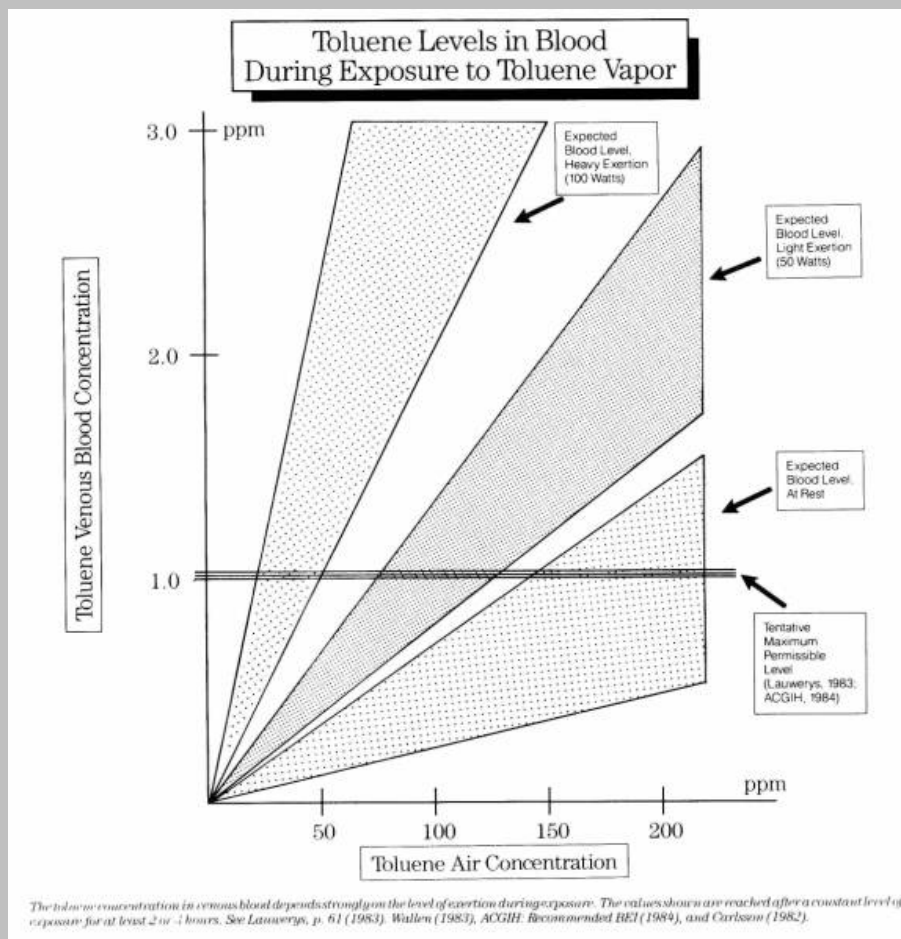
In this particular case the swimming "blitz" described at the beginning of the dive likely increased significantly alveolar ventilation and pulmonary blood flow delivering a higher dose of toluene to the brain. This relationship between physical activity (increased alveolar uptake and higher toluene tissue concentrations) and enhancement of the toxic effects of toluene can be seen in the figure below. This enhancement of toxic effects with physical activity would likely apply to any narcotic vapor contaminant and not just toluene found in the breathing gas supply. One might speculate on the potential outcome had this diver been 'bombing' a deep wreck to 10 atm with the same amount of toluene onboard. Having to swim against any current would have further enhanced the narcosis.

Given that many of these contamination events will present on descent or shortly thereafter depending on contaminant's partial pressure, duration of exposure, and physical activity it would seem prudent for technical divers to remain close to their buddy on descent so each other's physiological status can be monitored closely. A technical diver's descent should be considered a high risk time period for the presentation of potential gas contamination issues.

Although Barney did not experience any respiratory difficulties, toluene in sufficient concentrations or in sensitive individuals can cause respiratory distress leading to death. Wheezing from bronchospasm has been reported quite frequently and in high enough concentrations the lung's surfactant layer may be disrupted leading to pulmonary edema and respiratory failure. If concentrations are high enough direct CNS suppression of respiration will occur with hypoxia and hypercapnia followed by death.

Interestingly throughout the literature it has been observed that toluene sensitizes the heart to circulating catecholamines (epinephrine and norepinephrine). Several sources mentioned keeping the patient quiet and immobile for fear of provoking a lethal cardiac arrhythmia with severe overdoses, sudden movements, and increased myocardial irritability. Fatal arrhythmias such as ventricular fibrillation have been observed in animal experiments and conscious toluene overdose patients, and are thought to be due to a direct effect of toluene sensitizing the heart to circulating catecholamines especially if there is concurrent strenuous physical activity. It would be quite easy to see how such a toluene induced cardiac death in a diver, unless gas contamination was suspected, could be mistaken for a 'heart attack' or just be reported as a generic drowning with no antecedent cause identified.

In summary then Mike's symptoms are very consistent with a low to moderate level toluene exposure probably with the toxicity enhanced by his physical exertion early in the dive. It is possible there were other minor volatile contaminants involved with this incident, and the secondary gas analysis done by Analytical Chemists, Inc. of San Diego may yet reveal these with additional detailed analysis.



2) Toluene Source: Where did it come from?

As mentioned in several of the original posts on this thread one would have to consider an external source for the toluene contamination which would have been entrained into the compressor's intake. I have heard of one incident where this was the case with a remote intake located adjacent to a facility with 45 gallon drums of toluene used as industrial solvent. There are many incidents of BTEX (benzene, toluene, ethylbenzene, and xylene) contamination from an intake located near a fuel refilling station especially if the compressor is located in a marina. This gasoline vapor scenario with BTEX contamination is quite common in the dive industry and is why one should always check a fill station's remote inlet neighbors. Another external source of toluene could be recently used acrylic paints, glues, or cleaning solvents. Others familiar with the fill station in question have reported none of these potential external sources for toluene was an issue.

Prior to this incident I had been aware of some unpublished research done here in Canada on the subject of high pressure reciprocating breathing air compressor oil degradation at elevated temperatures which is what piqued my interest in this case. I mentioned this incident back in June to one of the persons who had been involved in this research and he asked to be kept apprised of the situation as it evolved. Once the contaminant was discovered I called him up and asked, "Guess what was found in the diver's tank?" His answer right off the bat was, "toluene" much to my surprise. Toluene in this previous research had not only been found by heating up compressor oils in the lab, but it had also been found in an air sample collected from a compressor installed in a very tiny room where the compressor had been suspected of overheating due to the poor setup and high ambient operating temperatures. Toluene was not the only volatile contaminant found by heating up these oils in the lab, but it was one of the most frequently encountered. Under the right thermal conditions lubricating oil may give off a volatile vapor from one of its original constituent components or form new pyrolytic vapor degradation products.

Subsequent to the above discussion a chemist/toxicologist was contacted who had done work and published several papers in peer reviewed journals looking at volatile pyrolytic degradation products of different jet engine lubrication oils. The airline industry about five years ago was having air contamination incidents with smoke and vapors entering the cabin air stream via leaking oil seals in

conjunction with the thermal breakdown of the jet engine oils, potentially impairing pilots and flight crew. After speaking with one of the scientists involved with this research he too felt toluene production from the thermal or oxidative breakdown of compressor lube oils was quite possible. This event would depend on the oil type and brand, the ambient compressor operating conditions (in particular high temperature), the FO₂ of the gas in the compressor as many of these breakdown reactions are oxidative, the amount of moisture in the oil, the length of time the oil had been used in extreme heat conditions, and interestingly what cylinder and piston ring breakdown products were in the oil at the time of the incident. Metals such as copper and iron which enter the oil sump from piston ring and cylinder wear/breakdown act as catalysts to many of these oxidative and pyrolytic reactions. He suggested that not only should the breathing gas be analyzed at the time of a contamination incident, but a sample of the used compressor oil be collected for analysis of its condition and for later thermal degradation studies in the lab. In other words just heating up the same brand and type of new oil from a compressor where contamination is suspected may not always yield the vapor contaminant(s) in question as the catalysts, moisture, and acids are missing which become part of the oil mixture with compressor use over time.

The possible production of compressor lube oil volatile hydrocarbons which may be toxic to divers is an area where a systematic study of all the commonly used oils needs to be done in an academic setting. The various synthetic diester and triester oils, and the newer ? safer polyalphaolefin (PAO) oils need to be thermally exposed at pressure with catalyst and oxygen in the case of continuous blending to see at what temperatures they start to breakdown and what may be the pyrolytic vapor degradation products. As with the jet oils, the temperatures reached and type and brand of oil are factors in these degradation products.

Why these studies have not been done to date by the oil lubrication companies themselves is a good question, but I suspect the answer I received from one oil company executive is quite representative. "Breathing air applications require a qualified filtration system to certify the oil for breathing air." In other words if you have proper filtration which is functioning it doesn't matter what the oil gives off at high temperature as the "qualified filtration system" will capture the contaminant. This may be partially true, however it would be prudent to know in the case of breathing gas production if a particular brand and type of oil when subjected to high temperature, pressure, FO₂, and wear gives off some toxic volatile vapor with a low margin of human toxicological safety should a filtration breakthrough occur. Also there may actually be certain contaminants produced from only certain brands or types of oil that are poorly removed from the air stream by standard scuba filtration or are very toxic and even with a "qualified filtration system" they present too high of a risk to divers to be used in breathing air production.

The lubrication companies seemed to have passed the buck on this one to the folks designing, operating, and maintaining the compressor and filtration systems we use. Their oils under certain thermal conditions may in fact produce toxic volatiles, but they feel as long as proper filtration exists there is no need to worry. This places a very large onus of responsibility on fill station operators to be aware of these heat related vapor risks, and to ensure a "qualified filtration system" does exist at all times between the diver and these potential contaminants. Unfortunately though most fill station operators are not well educated in these risks, and measures such as proper compressor installation, ventilation, and maintenance so as to prevent the oil overheating and volatilizing in the first place are not instituted. Under specific conditions therefore, and likely sporadically when a "qualified filtration system" suddenly becomes "unqualified" with a toxic volatile vapor present due to excessive oil temperatures, serious diver injury or death can occur.

Upon speaking with several of the lube oil companies they do see this issue as one mainly to do with compressor design and poor maintenance as well as inadequate and improperly maintained filtration. One oil company representative commented on the poorly designed small compressor oil sumps and volumes which lead to inadequate oil cooling and problems with oils overheating in the compressor system especially with extreme use in high temperature and humidity geographic regions. Another mentioned the large variations in frequency of oil change intervals between what they recommend and what the compressor manufacturers recommend. This particular company said synthetic oils should be changed out at 200 hours in normal conditions and at 50 to 100 hours in Nitrox blending situations or high ambient temperature and humidity conditions (those typically found at Florida stations during the summer). Running high FO₂ mixes through the oil substantially decreases the oil's life expectancy especially in conjunction with high temperature and humidity. As the oil starts to degrade irreversibly under these conditions the viscosity and acidity increase which leads to further compressor stage overheating and more oil thermal degradation and vapor risk as the oil loses its ability to dissipate frictional heat. The only way to determine the condition of an oil at any point in time is thru laboratory oil analysis which is a whole other science unto itself.

One wonders why all breathing air compressors are not required to have an oil temperature gauge and high oil temperature shut down switch. This would at least alert the fill station operator to conditions where thermal degradation conditions may start to occur. Bauer sells and sets its "optional" oil temperature alarm at 175 F. Ultrachem the manufacturer of Chemlube products states, "as temperatures increase the oil life is drastically decreased, especially above 220 F," and with its synthetic oil cuts the oil's life expectancy down drastically for each ten degrees above 180 F.

There is very good circumstantial evidence therefore that toluene can result from the thermal and/or oxidative degradation of a

compressor lube oil which will give rise to an internal compressor source of toluene contamination. The exact temperature and other conditions required (moisture, metal catalysts, etc.) for this reaction to occur however are not known at this time. It is very clear though that academic thermal laboratory studies are needed on these compressor lubrication oils both for the diester and triester synthetics, and for the newer food grade polyalphaolefins to determine what the potential toxic pyrolytic and oxidative degradation vapors may be for both the SCUBA and SCBA communities.

It would also be beneficial if an independent laboratory could do an analysis of the commonly used oils for high pressure reciprocating compressors examining how these oils wear over time with respect to oxidation resistance, water resistance, etc. Fill station owners would then not have to rely on potentially biased proprietary information from the oil manufacturers regarding an oil's suitability and life expectancy under typical and extreme (high heat) compressor conditions.

3) Toluene Filtration Breakthrough: How did it happen?

It is interesting to note that many of the experts I spoke with were not entirely surprised that toluene might appear in the pre-filtration gas stream as a lubricating oil thermal or pyrolytic vapor degradation product, but were quite surprised that the toluene vapor was able to get by the chemical filtration and end up in the diver's tank. In fact one scientist who works for the largest carbon manufacturer in the world and supplies coconut shell based activated carbon to Lawrence Factor and Bauer for their breathing gas filters summed it up very succinctly. He said, "The only way toluene ended up in the diver's tank was that the activated charcoal in the filtration was not just wet, but very wet probably well above the 80 percent humidity level." In other words the filtration was saturated with moisture and no longer protecting the gas stream from this contaminant at the particular time the tanks were filled. This was made quite clear by this scientist.

As he explained, activated charcoal will adsorb various vapors some very efficiently like toluene and some are poorly adsorbed like carbon dioxide (CO₂) and carbon monoxide (CO). In the case of CO we add Hopcalite to the filter cartridge before the charcoal bed in order to catalyze the oxidation reaction of CO to the less dangerous CO₂. This vapor adsorption by the charcoal bed depends on the size of the bed, the charcoal pore size relative to the molecule in question, the vapor pressure of gas, the polarizability of the molecule, the temperature of the gas stream, and the shape of the molecule with the aromatic hydrocarbons having the best adsorption of all. Toluene is an aromatic hydrocarbon and should normally be highly adsorbed by the activated charcoal. In this particular case though, the desiccant or sieve normally responsible for the absorption of water vapor from the gas stream must have become saturated allowing the charcoal bed's humidity to increase sufficiently such that it was no longer effective at removing the toluene from the gas stream. This phenomenon of a vapor passing directly through a bed of charcoal where normally the contaminant should be readily removed is known as "breakthrough".

So how might this happen you wonder and under what conditions? The question I kept getting asked by these scientists was at what ambient temperature was the compressor operating at the time of the incident? For this data I was pointed to the Florida Automated Weather Network (FAWN) which has historic climatic data and pulled up some interesting facts.

For the Gainesville area in northern Florida one can access on FAWN the number of hours a month that the temperature was above a particular threshold. For reasons that will become clearer below, I chose 65 F (18 C) as the threshold temperature which gave the following results:

Month.....	Percent Time in Month > 65 F
Jan.....	10
Feb.....	9
Mar.....	31
April.....	38
May.....	70
June.....	91
July.....	95
Aug.....	97
Sept	66
Oct.....	57
Nov.....	29
Dec (2003).....	5

If one looks at the daily temperature for the last Sunday in May 2004 (approximate date tank was filled) it ranged from 61 F to 96 F. At this time of year the temperature did not dip below 65 F until after 0100 hours and was above 65 F again by 0630 hours. By 0800 hours it was 80 F (27 C) and by 1400 hours the temperature hit a high of 96 F (36 C). These daytime temperatures would be classified as very high temperature ambient conditions, and the oil manufacturers would call these “extreme” conditions particularly if the compressor is set up in a small poorly ventilated room where ambient temps may be 10 to 20 F higher than the outdoor temperature due to the compressor’s own heat production.

In order to understand what likely happened to allow the toluene to breakthrough one must delve into (suggest coffee break now) how a cartridge’s processing capacity is determined by the manufacturers. When Bauer or Lawrence Factor (LF) report their respective filter cartridge processing capacities this is done at what’s called “standard inlet conditions.” Unfortunately these standard inlet conditions are not so standard between the filter manufacturers which has led to some filter brands reaching their maximal gas processing capacities much earlier than expected in high temperature ambient conditions. Once the maximal capacity is surpassed the desiccant can no longer keep the charcoal bed dry and vapor contaminant breakthrough will begin if the filter cartridge is not replaced. This is a very dangerous situation as what was previously a “qualified filtration system” has become “unqualified”, in other words no barrier exists to protect the diver from the vapor contaminants which may be present in the gas stream.

The filtration capacities are calculated assuming the gas entering the desiccant prior to the Hopcalite and activated charcoal is at a certain temperature and pressure, and is 100 percent saturated with water at that temperature. The relationship between temperature and the amount of water a kilogram of air can hold at 1 atm can be seen in the first graph below. The important point to notice is the exponential relationship between increasing temperature of the gas stream and the maximal amount of water vapor it will carry. One can see that the higher the temperature particularly above 65 F (18 C) the more moisture will be carried into the desiccant and as a result it will saturate much faster with increasing temperature. Molecular sieve 13, a commonly used desiccant to achieve very dry breathing gas, can hold about 20 percent of its weight in moisture, but as the gas stream rises above a certain temperature (> 120 F) the sieve will actually start to release some of its absorbed water back into the gas stream. Elevated temperature therefore increases the amount of water vapor carried in the gas stream to the desiccant, and if the inlet temperature is high enough this will also decrease the amount of moisture the desiccant can retain.

When it comes to calculating and rating the maximal cartridge processing capacity, by using a lower standard inlet temperature (less moisture entering the desiccant) as Bauer does, you actually get to advertise a higher filter capacity to the consumer. This creative accounting presents a very significant diver safety issue as with the Bauer cartridges although they have a higher advertised capacity at this lower inlet temperature, when they are used in high ambient temperature operating conditions above the standard inlet temperature these maximum filter processing capacities must be reduced by very large amounts. Very few Bauer filter sales personnel or fill station operators are aware of these vital temperature corrections to filtration capacity for elevated ambient temperatures, and therefore breakthrough of vapor contaminants becomes much more likely as the filter becomes saturated with moisture earlier than expected. Let’s have a closer look at how Bauer and LF determine their filter capacities.

Bauer calculates and rates its cartridge capacities at their “standard inlet temperature” of 68 F (20 C). Inlet temperature is the temperature of the air stream entering the chemical filtration or desiccant after the final oil/water separator. The difference between ambient and inlet temperature varies depending on compressor installation, ventilation, intercooler design, etc., but is somewhere in the 10 to 20 F range, so say 15 F.

Inlet temp = Ambient temp + 15F.

What this means is that when Bauer says the filter cartridge they just sold you is good for 40,000 cu. ft of gas processing this is only if an inlet temp of 68 F or an ambient temp of 53 F (12 C) is maintained in the compressor room. When was the last time you were at a fill station where the compressor saw a continuous ambient temp of 53 F while pumping?!! Certainly I have never seen one in the tropics, however I know several up here that never see an ambient temp above 68 F (20 C) as the compressor rooms are air conditioned. Lawrence Factor is a little more realistic with typical compressor room ambient temperatures as they rate their cartridge processing capacities at a standard inlet temp of 80 F (27 C) or an ambient temperature of 65 F (18 C) hence the reason I chose the Gainesville temperature threshold of 65 F.

One can see that any time the compressor’s inlet temperature is above the temperature where the cartridge capacity was determined a temperature correction must be made to reduce the filter’s capacity rating as the higher inlet temperature means more water vapor will enter the desiccant and it will saturate sooner. This translates into increased frequency of cartridge changes needed. Let’s have a look at just how often filter change intervals would have to decrease as the inlet temperature rises in a typical high heat geographical area.

From the northern Florida temperature data above and assuming most fill stations in this region are probably using the clear plastic LF

filters with maximum processing capacities set at 80 F inlet, one will need to make a capacity correction downwards any time the ambient temperature is above 65 F. One can see therefore that during the winter months of January and February a correction would only be needed 10 percent of the time, but during June through August a filter processing correction would be needed over 90 percent of the time if the compressor was used outside of the < 65 F time frame. With Bauer filters these corrections would be needed 100 percent of the time during the summer as an ambient temp of 53 F is never seen!

During the summer there may only be a four to five hour window in the early morning were a temperature of < 65 F actually exists. If one is using a commercial fill station which pumps high volumes of breathing gas they likely will not be able to meet customer demand especially on weekends pumping only during these few nighttime hours with lower ambient temps, and therefore much of the compressor usage time outside this cooler temperature window will necessitate corrections to the filtration capacity.

Using the Bauer filter temperature correction factors the extent of this problem of how easy it is to surpass cartridge processing capacity when used in high temperature ambient conditions becomes very evident. For a given filter capacity rating at standard inlet temp of 68 F (53 F ambient) here are the correction factors to multiply a filter's capacity ratings by depending on the actual inlet temps.

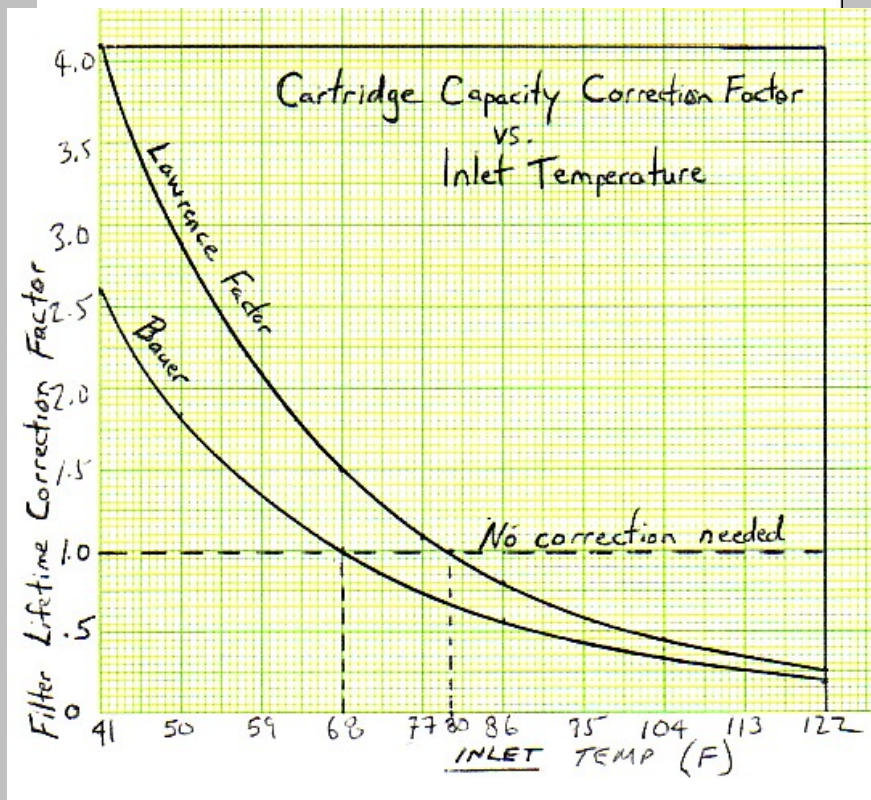
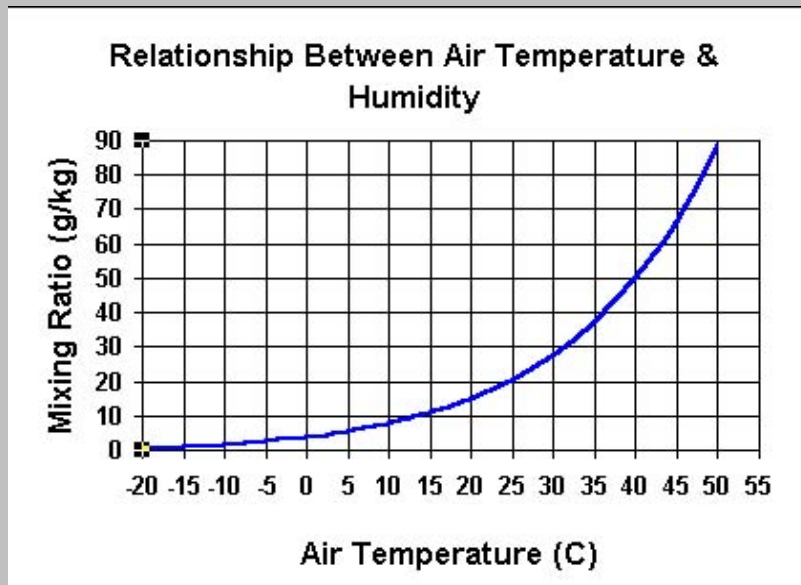
(68 F - 1)
 (86 F - .57)
 (104 F - .34)
 (122 F - .20)

At the end of May in northern Florida at 0700 hours with an ambient temperature of 70 F the correction would be .57 and by 1400 hours the capacity correction at 95 F ambient (inlet 110 F) is a whopping .25! If the compressor was run for two hours at 95 F this would have to be recorded as 8 hours of use in the log book as four times the moisture would be taken up by the sieve at this temp compared to 53 F. A typical 33 inch multiplex filter rated for 40,000 cu. ft of processing is only good for 10,000 cu. ft at an ambient temp of 95 F or one quarter of what its capacity is advertised for by Bauer. For the months of July through August a fill station would have to be switching out its filtration approximately two to four times as frequently than during the winter months. One can see then if an owner did not correct the filtration capacities for these high summer temperatures the desiccant and charcoal would become saturated well before the filters were changed based only on "standard inlet temperatures." Any vapor contaminant if present would therefore start to breakthrough and enter the storage banks and diver's fills. If a volatile vapor was present due to the thermal breakdown of the compressor's oil under the same high ambient temperature conditions, the gas would likely start to have an oily or solvent smell to it at this point in time.

With the LF filters the temperature correction factors are slightly lower as the standard inlet temp they use to rate their cartridges is higher to begin with. At the same inlet temp of 110 F an LF cartridge would require a correction to its capacity of about .4 compared to a Bauer factor of .25. (see 2nd graph)

As the only barrier that exists between a diver's tank and toluene or any other vapor contaminant present is the existence of functioning desiccant which continues to keep the activated charcoal and Hopcalite dry, it becomes imperative in any high heat geographic area, but particularly at those where commercial fill stations are pumping large volumes of gas on a daily basis to know exactly from hour to hour the state of their desiccant's saturation status. Otherwise, if the saturation status is not known in real time, once the charcoal becomes wet any vapor phase contaminant in the gas stream will begin to breakthrough the filtration contaminating the diver's fill and creating a high risk situation for diver injury. With high volume commercial fill stations this could happen very quickly before a problem was recognized.

One can see that as compressed breathing gas production moves from the small 'artisanal' or homebrewed means of production to one of large scale industrial production real time digital moisture and CO monitors should become mandatory at these large fill stations in order to protect the diver from sudden loss of a "qualified filtration system" and subsequent breakthrough of potential lube oil thermal degradation products into the fills. Many commercial fill stations may have made the leap to industrial quantities of breathing gas production without the necessary transition to proper industrial compressor installations where heat reduction becomes paramount, and monitoring of the gas stream quality occurs in real time using quantitative high pressure instruments. While the volume of gas produced may be at industrial levels at these high volume commercial fill stations often the monitoring of this gas quality remains at the "mom and pop" level.



After, a question came up from Oxyhacker:

I guess the big question is, that if this was a simple case of filter exhaustion, then wouldn't there have been a breakdown across the board in air quality, with oil and water present in such quantities that even a cut-rate analysis - or for that matter, a handkerchief test - could not have missed it? One would also assume that if this was the case it would have been easily noticeable afterwards when they returned to the shop - normally, one of the first things one does in a case of suspected contamination is check the filter condition

The answer was:

Very good question.

In the CGA Gd E analysis the oil and particulate analysis and the total volatile hydrocarbon analysis often lead to confusion as to what each tests for.

Oil and Particulate Analysis

The oil and particulate analysis looks for the condensable hydrocarbons or oil mist by trapping these on a filter paper, and then weighing this filter before and after the test to determine the final concentration of oil mist. Usually if the compressor is running too hot the oil is vaporized temporarily but condenses downstream in the tubing, banks, and your tank if in high enough concentration and with sufficient flow to keep it aerosolized and moving.

This same technique is what the military uses to create fog oil so as to obscure soldiers' movements. A mineral oil is poured into a heated manifold which vaporizes the oil and upon contact with the cooler atmosphere a condensation aerosol is formed. If you were filling right off the compressor which was running too hot you would likely get a similar fog oil aerosol in your tank, but overtime this would settle and stick to your tank walls. Once this hot oil vapor though hits the cold high pressure tubing, banks, fill whips, and finally possibly your tank it has condensed back to the same oil more or less as is in the compressor.

It would be possible to catch this mist on a hankerchief if in high enough concentrations and still present in an aerosol form but usually with time this mist will settle out and stick to the tubing and bank walls. This is why one needs a very high flow and of sufficient volume during sampling to mobilize these condensed oils. For this reason it is not possible to do a proper oil and particulate analysis off a scuba tank for forensic purposes as the scuba tank oil once on the tank walls cannot be remobilized for analysis. You need to go back to the original compressor system and flow at a minimum of 8 cfm for five or ten minutes to get the oils mobilized from the storage banks and tubing onto the filter paper.

This oil mist is also what one tries to minimize in the production of oxygen compatible air for PPM.

Total Volatile Hydrocarbons (TVHC)

These are not condensable oils and remain a vapor in the true sense of the word as they exist in the gas phase which is different than the liquid particulate or aerosol above. In this pyrolytic oil degradation incident above all the suspected lube oil volatile degradation products fall into this TVHC category. As they are volatiles they will not be trapped on a hankerchief or filter as they are gaseous. Toluene and all the BTEX compounds would be found in the TVHC analysis not oil and particulate analysis. These volatiles are identified with a gas chromatograph/mass spec whereas the oil mist analysis above is simply a gravimetric test, pre and post test filter weigh.

From a health standpoint high concentrations of oil mist which has a low vapor pressure will not enter the blood stream but will end up being deposited in your lungs and may cause a lipoid pneumonia well after your dive. You will come home at the end of the day but will likely develop a nasty cough in the subsequent days.

An elevated TVHC either from toluene or some other volatile organic hydrocarbon from the pyrolytic degradation of the lube oil is a much more serious issue. These vapors enter the blood stream rapidly and can cause narcosis and death depending on concentration, depth of the dive, exertion, and duration of exposure. They enter our CNS tissues rapidly and impair cognition. You may not come home from your dive with these onboard. A hankerchief will not find these volatile HCs but your nose will. Very low cost and low tech way to protect yourself 😊

As for the second part of your question it is a little more difficult to answer but I will give it a shot. Maybe Barney or Joe can chime in but I do recall one of them saying they returned to shop to speak with the person filling the tanks. Remember though there was a one month interval I think between the fill in question and the dive in question so the situation at the fill station at the time of the incident was likely not the same as when the fill was done a month prior, however they did detect a similar smell on some of the fill whips at this time.

Filtration breakthrough is a complicated business depending on numerous factors and I suspect is much like tornado prediction. We know the conditions a tornado is likely to form under but predicting where the first tornado will touch down is far more difficult.

Upon speaking with the the carbon scientist who also happened to be a diver as well and was most interested in this case, it became apparent that breakthrough is not an all or nothing event. Assume the desiccant is near saturation and the compressor is running at 1400 hours when the ambient temp is 95 F or likely well over a 100 F in the compressor room. The inlet temp will be even higher probably

pushing the 120F limit for the molecular sieve. All of a sudden the sieve gives off a burst of water vapor as its ability to retain water at this temp is compromised. The charcoal bed's humidity rises suddenly to a level where it can no longer adsorb the vapor contaminant efficiently and vapor breakthrough spikes start for the duration of the compressor run. If the compressor is run later at 0400 hours when things are cooler there may not be sufficient temperature to get pyrolysis of the oil and the sieve at the lower temperature is protecting the carbon again.

Alternatively one can have relatively dry charcoal but if the contaminant vapor is high enough or fluctuating breakthrough can occur. When the contaminant concentration is fluctuating rather than steady state the breakthrough spikes occur much earlier and at higher levels. This can be seen here in some work done at DCIEM. Figure 3 page 32 shows this effect.

<http://cradpdf.drdc-rddc.gc.ca/PDFS/zba15/p151935.pdf>

A rather long winded answer I know, but no the hankerchief will not find these volatile hydrocarbons however the nose may. It is possible to get breakthrough with dry carbon and fluctuating contaminant levels, or from wet carbon that is no longer effective which is the more common scenario. The latter situation would occur in high temp regions where there was no attempt by a fill station operator to monitor desiccant saturation status.

The simple answer to all these problems is keep compressor heat (now a four letter word I hope) down at all costs and why Bauer is "rabid" about compressor installation and ventilation.

4) Determining Desiccant Saturation Status

If the only thing keeping a diver from being poisoned is a "qualified filtration system" between you and potential gas stream contaminants then the first question an educated diver should ask a fill station owner is, "How do you determine when your filtration is saturated with moisture?" If the owner gives you a blank stare then the next question you should ask is, "When did you last change your filtration?", especially if in Florida between May and September! If he says yesterday then you are probably safe, but if he says eight weeks ago you probably want to be careful if it is a high volume station during a heat wave at the end of a busy weekend.

It should be very apparent now why all fill station operators should have some method of determining the moisture saturation status of their filtration if they are to prevent these contaminant vapor breakthrough incidents from occurring. Sadly most do not make these filtration processing capacity temperature corrections or do not have a real time device to determine saturation status. This is often the case because these operators have not been educated either by their compressor or filtration manufacturer on the importance of these issues, and there are very few courses or certifications where one can go to learn the ABCs of safe gas production covering everything from compressor installation to breathing gas analysis. To add to the problem a moisture analysis is not even required as part of the CGA Grade E standard air analysis (one is required under Canadian CSA Z180.1 analysis) so it is possible a fill station could have absolutely no idea as to the moisture status of its filtration at any point in time other than using the hour meter and filter capacity rating at standard inlet conditions. Think of these issues the next time you visit Mexico's Yucatan Peninsula or Palau and there is no air quality assurance program period, no temperature corrections being done, or no real time monitor to determine moisture saturation status of the filtration, yet they are filling 500 AL80's a week in a tiny compressor room with inadequate ventilation. These types of geographic locations with year round high heat conditions, lots of diver traffic, and no monitoring of filtration status other than the hour meter represent high risk fill stations for gas contamination incidents.

So what methods are available to detect moisture levels in filtration? Here is a brief description of the current methods from the low tech, low cost to the high tech, high cost. The home brewer or 100 hour a year fill station can stick to the low tech gear, but as one gets into pumping 40,000 cu. ft of gas a week especially in high temperature climates, the high tech devices should be required to protect the diver's gas supply from filtration moisture saturation and contaminant breakthroughs.

Current methods available for saturation status determination

1) Temperature logging

One logs temperatures by the hours of compressor use and then applies the correction factor to increase the number of hours for the higher saturation rate. This method is tedious but would be suitable for home and smaller fill stations. Very low tech and free of charge.

Example (Bauer filters and ambient temp)

Logbook for May 25

95 F 2 hours $2/.25 = 8$ hours

70 F 6 hours $6/.57 = 11$ hours

So 8 hours of actual use is now corrected to 19 hours towards the rated maximal processing capacity at standard inlet conditions.

2) Filter with visible humidity strip

Lawrence Factor cartridges which are clear plastic have a humidity strip on the inside which changes from blue to pink when the relative humidity reaches 40% at pressure. This corresponds to a dewpoint of about -40 F at which point the filtration should be changed out in warmer climates.

In colder climates where one is concerned with freeflows during cold water diving the dewpoint needs to be much lower than -40 F usually at least -65 F (-53 C), and filtration would need to be changed much earlier so as to maintain sufficiently dry breathing gas. See method 4 or 5 below for what to do in this coldwater case.

The only problem with this humidity strip method is one has to take the actual cartridge out of the filter appliance in order to see the humidity strip, but at least there is some real time potential. The danger though is if one doesn't also correct for high ambient temperatures while using the humidity strip, it will turn pink well before the fill station owner figures it is time to check the cartridge leading to loss of "qualified filtration" and gas stream contaminant protection. This situation of having the humidity strip inside the filter stack is akin to having your car's gas gauge inside the trunk of the vehicle. At some point the operator will be too lazy or forget to check the gauge and the car will run out of gas. A filter humidity strip will though provide an additional check to your temperature adjustments if logging compressor hours.

3) External visual humidity detector

Combining an external visual humidity detector either after the first desiccant only filter or after the last triple media filter (desiccant/Hopcalite/ activated charcoal) with the LF humidity strip above is probably the cheapest and most reliable low tech, low cost way to go. Definitely with the filter cartridges such as the aluminum Bauer ones which don't have a humidity strip this device should be the bare minimum standard and should be used in conjunction with temperature corrections as a secondary real time back up.

Every commercial fill station should have one of these detectors for humidity as a bare minimum to get an idea as to what the filtration saturation is doing in real time. Temperature corrections can be off during heat waves and often inlet temperatures can be higher than calculated. This simple low tech, low cost device provides decent real time moisture check without removing the cartridge. Essentially this moves the car's gas gauge out of the trunk back onto the dash where it should be. For homebrewers who are packing their own filter stacks with media this little device would also allow one to judge when the desiccant is saturated again though for warm water diving.

The device only costs \$80 US and is available from GMC Scuba (part #44070). The replacement sensor elements (#44071) with the humidity ring and CO sensor dot in the center are about \$8 and should be replaced yearly. The humidity sensor ring changes color at 40 % RH or about -40 F (-40 C) at 3000 psi, similar to the LF filter humidity strip above. www.gmcscuba.com

4) Colormetric Tubes

Often known as ' Draeger ' tubes these tubes are available to measure moisture down to extremely low levels. There are several kits on the market which can measure CO, CO₂, moisture, and oil vapor simultaneously, but these multigas field analysis kits are not cheap, usually in the range of \$800 to \$2500 US. Several of the breathing gas laboratories if using their services should be able to provide a moisture only colormetric device for considerably less. One would then do serial dewpoint measurements and change out the filtration when the dewpoint approached what was determined acceptable for the dive conditions. As mentioned above at a cold water dive fill station one would want to think about switching out the filtration when the dewpoint had reached -65 F (-53 C) so as to minimize freeflows. In water near the freezing point a dewpoint usually in the -90 F (-70 C) range or drier is recommended. In these cold water conditions the visual humidity detector above would not be adequate to ensure dry air.

5) Inline real time dewpoint meter

The highest level of protection involves considerably more money and maintenance, but these high pressure inline dewpoint (and CO) meters available from Cosa Instruments or Nyad Inc. will give you real time digital dewpoint readings. The units though do require

regular calibration to maintain accuracy. Any commercial scuba station especially those in the industrial category pumping high volumes of gas in high temperature geographic regions should have one of these real time dewpoint meters on their breathing gas systems in order to monitor moisture status and ensure there is a “qualified filtration system” present at all times. With these devices one no longer must rely on temperature corrections and when filling banks around the clock one can just check the meter and see exactly where either the pressure or atmospheric dewpoint is sitting.

www.nyad.com/Series_600.html

5) Prevention of Gas Contaminant Episodes and Assessment of a Fill Station's Potential Contaminant Risk

What should be fairly clear now I hope is why HEAT is a four letter word in the compressed breathing gas production business. If an ounce of prevention is worth a pound of cure then that ounce is simply keeping the oil and filtration inlet temperatures as low as possible during compressor operation.

In summary then, in order for this toluene incident to have occurred two conditions were met simultaneously which allowed the diver's tank to become contaminated. Remember contamination will not necessarily occur if the oil degrades and there is a good filtration barrier to capture these new degradation vapors. Likewise if the filtration saturates just through normal use at low ambient temperatures there may be no danger if the gas stream remains contaminant free.

1) OIL BREAKDOWN: The lubrication oil degraded likely due to oxidative and/or thermal breakdown producing the narcotic gaseous vapor toluene. It should be noted these are new gas phase vapors formed by the pyrolysis of the lube oil and are not thought to be part of the original oil or its light chain odor vapors. The new vapor formation is dependent on the original oil's composition which includes base stock and additives. This original oil plus the wear and tear additions of acidity, moisture, and metallic cylinder breakdown products allows the production of new thermal degradation products such as toluene when this mixture is exposed to high heat, pressure, and hyperoxic environments in the compressor system. Unlike the original oil which may vaporize if overheated and condense into an oil mist downstream in the compressor system, these new degradation vapors remain in the gas phase and are not found in the CGA Gd. E oil and particulate analysis. They would likely show up in the total volatile hydrocarbon analysis.

2) FILTRATION BREAKTHROUGH: In order for the toluene produced to breakthrough the activated charcoal bed the desiccant must become saturated with moisture usually from excessive inlet temperatures. The humidity level in the charcoal bed reaches a critical moisture level and breakthrough spikes begin allowing the toluene to enter the storage banks or individual tanks if filling directly off the compressor. This critical moisture breakthrough level is different for each gaseous contaminant and also depends on numerous other factors such as whether the vapor concentration in the gas stream is steady or fluctuating.

I have tried to think of a good analogy that divers might remember so as to reinforce the dangers of operating a compressor with a compromised filtration barrier, and also be one which might approximate the health risk that exists when contamination does occur due to the loss of qualified filtration.

One might want to consider what happens when your dentist's sterilizer goes down for a day or two without the dentist knowing. Normally the only barrier that exists between you in the dentist's chair and the previous patients' blood borne diseases is a properly functioning instrument sterilizer. When that sterilizer malfunctions unless the previous patients were all nuns then chances are with a day's worth of dental patients that several of these patients will have a transmissible blood borne disease. If the instruments remain contaminated due to loss of sterilization there is a good chance you will become infected and sick at a later date. Office sterilizers are usually checked monthly in an ideal world for proper functioning but do malfunction sporadically for various reasons. When sterilization does not occur adequately one will get sporadic disease transmission within medical and dental patient populations. These diseases are often serious and potentially lethal.

Likewise with a breathing gas compressor system the only barrier between you the diver and any vapor contaminant such as CO, CO₂, or narcotic vapors such as toluene from the thermal breakdown of an oil is a proper functioning filtration system. Once this filtration goes down and one of these contaminants is present in the gas stream, there is no better way of delivering this contaminant rapidly to your tissues than by inhalation at high partial pressures. If the contaminant partial pressure is high enough and the exposure of sufficient duration you may die early in your dive on descent, or sometime thereafter as exposure duration increases. If a thermal degradation vapor was the cause of death chances are the death certificate or coroner's report will not reflect the true chain of events which lead to your demise. Drowning, heart attack, and physiological causes come to mind.

If you don't like the idea of going to your dentist without a functioning sterilizer between her last patient and your blood stream, then you should be far more concerned at any fill station where the proper functioning of the only barrier between you and potential gas stream contaminants is undeterminable, or left in the hands of an operator who is unaware of the potential health risks to the diver should this barrier become compromised.

A functioning filtration system therefore needs to be verified in real time each time the compressor is running especially in geographical locales with high ambient heat where desiccant saturation is much more rapid. If not verifiable, just remind yourself of that dentist with the broken sterilizer who had a few IV drug users as patients the day before you arrive! A compressor's filtration system is in effect our gas "sterilizer" so as to prevent gas borne disease.

Assessment of Compressor Station Potential Contaminant Risk

Let's assume we arrive on holidays to do some deep technical diving in Palau (average yearly temp is 82 F with 85 percent humidity). At the local fill station we wonder how can I assess the quality of the air that is going to be used for partial pressure mixing or continuous blending? What can a diver look for at the fill station to determine the potential gas contamination risk? While walking around the compressor system setup it should be clear now that minimizing heat in the system is the name of the game, and the identification of poor installations where overheating is likely should raise lots of red flags.

1) Geography and climate.

Any area with sustained high heat and humidity will be higher risk for contamination episodes so one needs to be much more careful in these areas. Excessive heat leads to oil pyrolysis and faster filtration moisture saturation. The safety margins are much smaller for poor compressor installations and/or poor maintenance in high heat and humidity locales. Remember if ambient is 90 F outside the compressor room then after an hour of operation in a tiny room with no cross ventilation the ambient temperatures can easily be over 100 F, and your inlet temperature will be 15 F higher than that. If the intake for the compressor is not located outside this room then the compressor will entrain hotter and hotter air as that room heats up. Filtration saturates very quickly in these conditions often five times faster than at standard inlet conditions and ultimately the desiccant starts to release moisture previously contained.

2) Inspect the compressor set up

a) the remote intake if present should be of large diameter ideally 3 inches or greater with minimal elbows and the shortest possible length. Long narrow intakes lead to compressor overheating. It is the radius of the intake that mainly determines resistance to flow. When you see long narrow intakes often with a clogged debris filter on the end think of the compressor having to breathe through a long narrow straw.

b) check what is around the intake: fuel refilling stations and vehicles nearby should be red flags if a remote intake

c) most important is the compressor's room size and ventilation. If the ambient temp is 90 F and you walk into the room with the compressor running and it feels much warmer then you really want to determine how the owner is assessing the moisture saturation status. There shouldn't be more than one compressor in the room running at the same time unless proper ventilation exists. Remember those LF filter capacities are determined at an ambient temperature of 65 F and the Bauer ones at 53 F. Bauer suggests allowing 1100 cu. feet minimum for a typical SCUBA compressor room with lots of cross ventilation and if the room is smaller there should be a proper high capacity exhaust fan or ideally the room cooled with air conditioning (see link) Many of the large SCBA stations are now air conditioned so as to maintain inlet temps at 80 F (ambient 65 F). <http://thedecostop.com/forums/showpost.php?p=140916&postcount=44>

d) If the compressor is against a wall with no intake vent in that wall at least 18 inches should exist between the wall and the compressor fan, 36 inches is better.

e) If you are in a high heat region and at a busy fill station you want to see lots of filtration towers probably a minimum of three 33 inch towers after the final separator. If you only see one or two 33 inch filtration towers you know the those filters are going to require close monitoring for moisture saturation status and frequent changes. Think about that dentist with no sterilizer!

3) Ask for the most recent air certificate.

Not terribly useful if being done quarterly and the last one was done three months prior to your arrival. In fact it is just about useless for determining anything three months after the fact. If there is no moisture analysis it even is less useful. An air analysis is really only representative of the gas quality on the day it was done and much can change in that three month interval such as a long heat wave and/or the oil reaching the end of its useful life.

4) How is filtration saturation status being determined?

If there is no certificate as is often the case at these tropical dive fill stations then the most crucial piece of data you can determine is when the filtration was last changed and what the owner is doing to determine when the next change is required. As mentioned previously, if there are no temperature corrections being done, no humidity strips on the cartridge, or no inline eyeball humidity detector then one should be very careful if the filtration has not been changed for sometime, especially if planning to head to 10 atm. If deep technical diving and there with a group you might even offer to pay for a filter change if you didn't like what you saw at the fill station. At least if you see new filters go into the stacks then even if the oil is too hot and starts to degrade there will be a barrier of "qualified filtration" between you and any gas stream contaminant for your week of diving.

5) Ask when the fill station manager fills his storage banks.

You don't want to hear the compressor running in the noon day sun but rather after midnight when the ambient temps are coolest. Those correction factors are lowest at this time and the cooler temperatures will prolong filtration life and minimize the potential for oil thermal degradation.

6) High air and oil temperature alarms

In an ideal world all compressors should have these with a shutdown switch. Our cars have temperature gauges so one wonders why on a breathing air compressor this is not standard gear as well. In Canada the most recent breathing air standard now requires high air temperature alarms on all compressor systems. There is usually a sensor in the final stage head which will shut down the compressor if running too hot.

Tank Field Checks

1) Last but not least even after this walk around assessment of the fill station use can your high tech, low cost nose to field test each and every tank especially if you detect a fill station that looks high risk. Your nose should be able to detect low levels of volatile hydrocarbons in the gas and at least warn you about a problem before diving in. If in doubt ask someone else to smell the tank and if still in doubt don't dive period. A heavily contaminated tank on descent may kill you in a few minutes at 10 atm especially if working against a current. You can be assured that any fatality investigation in a place like Palau will not involve a proper forensic gas analysis and the death certificate will likely report a heart attack or drowning. It is therefore up to the educated diver to identify and avoid high risk fill stations ahead of time so as to prevent these incidents.

2) Carry a portable low reading quantitative (0 to 70 ppm) carbon monoxide detector to fill stations you are unfamiliar with. They can be had for \$80 and are cheap insurance against this odorless, irritantless, and colorless potentially lethal contaminant. If there is > 2 ppm CO I'd be very suspect about other contaminants being present like CO₂ or some volatile narcotic vapor. It is also not uncommon in some of these tropical locations off the beaten path to find filtration that has no Hopcalite in the cartridge to convert any CO in the gas stream to carbon dioxide.

6) Future Research Needed and Forensic Gas Analysis

Research into diver's air/gas quality over the years has been woefully inadequate. One is hard pressed to find any studies systematically looking at gas contamination incidents likely because there seems to be a bias in belief that these incidents occur so infrequently as to be insignificant. The problem though is unless one does a forensic gas analysis in all dive fatalities it will remain unknown whether a gas contamination problem was the true initial injury and first event in the chain which led to, for example, the seizure or respiratory distress on descent, the disorientation in a cave and subsequent drowning, or the chest pain and pulmonary barotrauma from a rapid ascent. If we don't consider gas quality problems as a possible initial injury event from which many of the other injury categories may follow, then the status quo of reporting these likely sporadic gas contamination fatalities as heart attacks or drownings of unknown cause will only continue.

In fact, if one examines the DAN fatality data for the years 1995 to 2000 twenty-eight percent or 145 fatalities (approx. 30 fatalities a year) are recorded as a near-drowning or drowning with the initial injury “unknown.” That is a very large number of fatalities year after year with no antecedent cause identified, and no research into what might be the injury mechanisms behind this category of unknown drownings. I think it is quite easy to speculate given the degree of cognitive impairment Barney experienced in this incident that had the initial toluene concentration been higher, or at a higher partial pressure at depth the ending may not have been as benign as it turned out. One suspects in this incident had the outcome been a fatality with only the first gas analysis done that there would have been yet another drowning of “unknown” cause added to the DAN statistics.

Better data needs to be kept on the events which occur prior to a drowning or near drowning incident. Antecedent details such as what was happening on descent with regard to the diver’s behavior and respiration need to be recorded as it is during the descent when many of these contamination episodes will present. Was the diver panicky and anxious indicating a possible CO₂ incident, or was she dream-like and drowsy before spitting the regulator out for no reason indicating a possible narcotic vapor in the gas supply?

It is probable these gas contamination fatalities are sporadic and occur only when a sufficient number of fill station risk factors as described above coincide together in conjunction with a sensitive diver whose individual predisposition depends on many factors such as age, fitness, smoker, medications, etc. As mentioned earlier, the technical diver will always remain a very sensitive “canary” for these contamination problems due to the high partial pressure contaminant exposures at depth. The time may have arrived for divers to encourage DAN to begin looking at this issue of SCUBA compressed gas quality a little more seriously by committing some resources for research studies into this topic. Improved breathing gas quality may in fact remain one of the last frontiers of dive safety overlooked by the industry, and with improvements in this area a significant drop in the numbers of fatalities may occur worldwide.

If you ever find yourself involved with a fatality investigation insist as the diver’s buddy or family member that a forensic gas analysis be done by an accredited lab which participates in the Compressed Air Proficiency Testing (CAPT) program. The CAPT program is a quarterly testing program done by a university third party laboratory to ensure the lab you use is producing reliable results for the gaseous components of the analysis (moisture, oil and particulates are not part of the program). The US Navy requires all its external contract and specialty labs to use the CAPT program and at this point in time the Navy uses Analytical Chemists, Inc. (ACI) in San Diego, and TRI Air Testing Inc. in Texas for the bulk of their outside testing.

Remember a gas sample should be taken as soon as possible after the incident as some of these degradation vapors may be unstable over time which will lead to a drop in their concentration the longer the gas sits in the tank. Likewise the sample once taken should be forwarded to the lab without delay. A moisture analysis should always be requested as an elevated dewpoint may indicate the filtration was sufficiently saturated to allow the contaminant to breakthrough into the gas stream and storage banks. A sampling kit from ACI as shown in the thread photos could be sent by overnight express to any global location in order to assist the local authorities if a high quality breathing gas lab was not available. The sample flask is low pressure so it can travel by air without any restrictions.

Although possibly difficult to obtain under these circumstances, in the event of a fatality where gas contamination is suspected one should try and take a small (50 cc) compressor oil sample from the system where the gas originated from. This oil could be heated up at a later date and again be used for forensic analysis into the origin of a toxic degradation vapor.

One of the high priority areas of research which needs to be done in an academic setting is a study looking at the pyrolytic degradation vapors of the commonly used compressor lube oils such as Chemlube 751, 800, Summit DSL-125, and the newer PAO oils such as EZ-1000 and CF-2000. Not only would the unused oils need to be exposed to heat, pressure, and O₂ similar to those found in an overheated compressor system, but also oils that have come from extensive use in the field under real conditions of high heat with all their ‘wear and tear’ components need to be heated up in the lab as well. These used oils may produce a different set of new degradation vapors not found with the unused oils. As mentioned previously there is already a group of physicians, toxicologists, and chemists who have been involved in researching similar problems of air contamination in the aviation industry from degradation of jet engine lube oils, and whose expertise could be used to investigate our compressor lube oil concerns and SCUBA breathing gas quality. The SCBA community is also very interested in these problems as well, but more from a chronic exposure standpoint to these potential breathing air contaminants.

As for compressor filtration it is time to put an end to the creative accounting with the advertised maximum processing capacities and have all the filter manufacturers rate their filters at the same “standard inlet conditions” using a realistic inlet temperature. My suggestion as the bulk of diving does occur in warmer parts of the globe would be to standardize at an inlet temperature of at least 85 F (29 C) which gives an ambient of 70 F (21 C) for the compressor room. For Bauer to standardize their filter capacities at an inlet temperature of 65 F is at best misleading, and very much a diver safety issue especially when the company and filter resellers do not seem to educate the fill station managers purchasing the filters about the need to make the huge capacity reductions in high heat climates.

All commercial fill stations must have a method to determine in real time the moisture saturation status of their filtration especially in the high heat geographic areas where filtration will saturate much more quickly. An eyeball humidity detector with manual temperature corrections or filter humidity strips should be a basic requirement on all compressor systems. The installation of oil and air high temperature alarms with shutdown switches should be considered mandatory with large commercial fill stations in tropical regions as should the installation of real time digital moisture and CO meters when the quantity of gas pumped is in the industrial range. Greater education and possibly standards regarding the proper installation of breathing air compressor systems in order to minimize overheating should be considered as basic preventative measures against gas contamination incidents.

Lastly some serious consideration should be given to the establishment of a commercial fill station operator's certification course which would cover the ABCs of proper compressor plumbing, installation, and maintenance through to the science of breathing gas analysis. It should be emphasized in such a course that a proper functioning filtration system is the diver's gas "sterilizer", and this filtration should be maintained with the same degree of care one would expect for a medical instrument sterilizer as the health risks with a malfunction in either system would be similar and potentially lethal. Whether such a certification course should evolve from the compressor manufacturers themselves, an organization such as PSI, or a government agency would need to be debated.

With a future fill station manager's certification course hopefully all those neglected dirty compressor systems kept in tiny, dank, and excessively hot backrooms until now would finally be given the priority and importance these 'systems' deserve. The diver's breathing gas compressor system is the most important piece of equipment in which one must have full confidence, even ahead of all the other safety concerns such as adequate training and gear quality. If not, then the first event in that proverbial chain may often be contaminated gas despite having the best equipment and hundreds of hours of training.

Next some pictures submitted by Barney of the sampling process.





Article edited by [Cristián D. Pittaro](http://www.neptunoworld.com) from www.neptunoworld.com