Designing for IAQ In Natatoriums

By Randy C. Baxter

In the last 10 to 15 years research has shown that poor air quality in indoor swimming pools has a negative impact on the health of swimmers, coaches and pool workers. Poor indoor pool air quality, caused by compounds off-gassing from pool water, has been linked to eye, nose and throat irritation, exacerbation of asthma symptoms, as well as to a predisposition to develop bronchial hyperactivity and asthma.[1-4] These health concerns are in addition to the well-known damaging effects of the indoor pool atmosphere on pool buildings and equipment.[5]

The purpose of this article is to review the literature concerning the effects of disinfectant by-products on indoor swimming pool air quality and to propose practical methods for mitigating their impact in conventional (recreational and competition) indoor pools.

Trichloramine & Other By-Products

The literature is very clear that, of all the disinfectant by-products (DBPs) present in the pool atmosphere, trichloramine vapor (nitrogen trichloride) is the primary compound responsible for indoor pool air quality problems that cause adverse physiological responses in humans.[1-4,6] Other inorganic chloramines (mono- and dichloramine), as well as related organic DBPs are also present in chlorine-disinfected pool water and pool air.[1] These DBPs include trihalomethanes (such as chloroform), haloacetic acids and other compounds including haloketones, trichloroaldehydes, trichloronitromethane, and cyanogen chloride.[7] Organic DBPs have not been found to cause adverse physiological response or discomfort in the concentrations found in indoor swim-

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Discomfort or physiological response to trichloramine exposure ranges from sneezing, coughing, and irritated eyes to wheezing, breathing difficulty, chest tightness and chest congestion to increased risk for asthma.

ming pool air although some have been identified as potential human carcinogens.[8]

For the purpose of this article, only the inorganic chloramines will be considered. It is logical to assert that a strategy that removes inorganic chloramines will also be effective in mitigating the impact of related DBPs.

Monochloramine is the most well-known and most prevalent inorganic chloramine. It is always present in chlorine-disinfected water and is frequently used by municipal water systems as a secondary disinfectant.[9] Monochloramine does not irritate the eyes or respiratory system and, in normal concentrations, it is not a significant cause of air quality problems in the indoor pool environment.[10]

Dichloramine is more volatile and more irritating to the respiratory system than monochloramine, but it does not persist as a vapor in the air[2] and decomposes rapidly in water.[11] Dichloramine does not contribute significantly to air quality problems but it is associated with undesirable taste and odor in water.[12]

Trichloramine, on the other hand, is a potent respiratory irritant; its effect on the respiratory system and eyes is similar to that of chlorine gas.[1] Because of its toxicity and the fact that it can exist as a vapor in the air, most experts agree that trichloramine is the compound most responsible for the indoor pool air quality problem.[2,4] According to Black & Veatch,[12] trichloramine is the only species of combined chlorine that causes tearing of the eyes.

Trichloramine Formation

Inorganic chloramines are a by-product of chlorine disinfection of water that contains nitrogenous organic material.[6,9,10,12] Three inorganic chloramines can be formed as disinfection by-products: monochloramine, dichloramine and trichloramine. The definitive mechanism of trichloramine formation in swimming pool water is not universally agreed. One accepted mechanism of trichloramine formation is by a series of pH-dependent substitution reactions:

At normal pool pH:

$$NH_3 + HOCl \rightarrow NH_2Cl \text{ (monochloramine)} + H_2O$$

At pH < 7:

$$NH_2Cl + HOCl \rightarrow NHCl_2 \text{ (dichloramine)} + H_2O$$

At pH < 4.4:

$$NHCl_2 + HOCl \rightarrow NCl_3 \text{ (trichloramine)} + H_2O$$

The above mechanism requires acidic conditions and precludes the formation of trichloramine in swimming pool waters that are maintained within normal (7.2–7.6) pH limits. But Holtzwarth[13] found that even at near neutral pH, a high Cl_2:N ratio enables the reaction of free chlorine and dichloramine to proceed:

At high Cl_2:N ratio:

$$NHCl_2 + HOCl \rightarrow NCl_3 \text{ (trichloramine)} + H_2O$$

Researchers Blatchley and Li[9] and Schmalz, et al.,[14] also found that the reaction of organic nitrogen compounds (such as urea) with free chlorine forms trichloramine at the normal pH values found in swimming pools. There is evidence that trichloramine can be formed when a pool is operated at breakpoint conditions, especially when there is organic nitrogen in the water.[12]

Despite the lack of consensus as to the definitive mechanism of trichloramine formation in pool water, there is no lack of evidence of trichloramine vapor in the air above indoor swimming pools.[2,14] Hery[2] found airborne trichloramine concentrations of 0.05–1.94 mg/m^3 in 13 swimming pools tested. Massin[4] measured trichloramine in 46 public swimming pools and 17 leisure pools and found average trichloramine concentrations of 0.24±0.37 (standard deviation) mg/m^3 and 0.67±0.17 (standard deviation) mg/m^3, respectively. Stottmeister and Voigt[10] measured trichloramine concentrations as high as 18.8 mg/m^3. Jacobs[3] studied 38 indoor pools and found a mean trichloramine concentration of 0.56 mg/m^3 with a maximum of 1.34 mg/m^3.

Trichloramine is Irritating and Difficult to Remove

Trichloramine is extremely volatile and immiscible in water and it readily escapes the pool water, especially when disturbed. Formation, volatilization and release of trichloramine vapor into the air typically occur during times of increased occupancy because of increased surface film area and bather soiling load. Release of trichloramine vapor is exacerbated by heavy activity such as kicking and splashing.[6,10]

Trichloramine vapor causes discomfort in most people exposed to air concentrations of 0.50 mg/m^3 or greater.[2] Discomfort or physiological response to trichloramine exposure ranges from sneezing, coughing, and irritated eyes to wheezing, breathing difficulty, chest tightness and chest congestion to increased risk for asthma.[3] Positive dose effects of trichlo-

Chloramine Species	Solubility	Volatility (Henry's Law Constant)	Irritability of Vapor	Vapor Density (Ref. to Air)	Most Likely Location
Monochloramine	Soluble	0.45	None	Lighter than Air	In Water
Dichloramine	Soluble	1.52	Moderate	Unknown	In Water
Trichloramine	Insoluble	435	Severe	*4.1-5.8 kg/m^3	Above Water
Dry Air 68°F (ref)				1.204 kg/m^3	

* Trichloramine vapor density is estimated from the vapor density of similar organic compounds such as chloroform and perchloroethylene. Pure trichloramine vapor density has not been measured because of its explosive properties.

Table 1: Select physical and chemical characteristics of the three inorganic chloramines.[13,16]

ramine exposure have been reported on serum surfactant proteins, which are markers for lung epithelial cell injury.[1,3]

Table 1 summarizes select physical and chemical characteristics of the three inorganic chloramines. Volatilized trichloramine is a heavy gas with a density several times that of dry air. Its Henry's Law constant is approximately 100 times that of monochloramine. Trichloramine vapor that escapes the pool water initially accumulates in low-lying places and the lowest place in most pools is the space above the water line and below the deck level. Trichloramine settling in this area is referred to as the "chloramine bubble." The high vapor density characteristic that causes trichloramine to accumulate in low-lying places also makes it difficult to remove.

Existing Strategies to Improve Indoor Pool Air Quality

In the past virtually all efforts to deal with the indoor pool environment have focused on three areas:

1. Bullet-proofing pool buildings and equipment to prevent corrosive damage;
2. Dilution of the bad pool air with outside air (solution by dilution); and
3. UV treatment to reduce combined chlorine levels in pool water.

The use of corrosion-resistant material and/or coatings in pool buildings and equipment is effective in protecting structures, but does nothing to improve the indoor pool environment. High flow HVAC systems, using large amounts of ven-

tilation air to dilute the indoor pool atmosphere, can improve air quality.[10] Medium-pressure UV systems can reduce the levels of combined chlorine in the water.[9] But these systems are not a total solution to the problem as evidenced by the fact that modern indoor pools using these technologies continue to face periodic air quality crises that raise health concerns.[6] Why have these technologies and strategies been unable to solve the indoor pool air quality problem?

Most modern pool HVAC systems are designed to limit air velocity across the pool surface; this limited air movement is usually not sufficient to dislodge and lift (to the air return) the dense trichloramine bubble. If air velocity is increased enough to dislodge the bubble, then swimmer chilling, increased rate of pool water evaporation, and increased rate of trichloramine release become problems.[15] If the air velocity used is not sufficient to remove trichloramine at a rate exceeding the formation rate, then air circulation and dilution will only succeed in continuously circulating irritating trichloramine throughout the HVAC system and natatorium. The use of recirculated air plus ventilation air to clear the pool surface of trichloramine becomes a very delicate balancing act. Too little air movement allows the trichloramine concentration to build; too much air movement increases evaporation and reduces swimmer comfort. Whether or not the air velocity needed to clear the trichloramine falls below the velocity across the water at which other problems start to appear depends very much on individual natatorium and HVAC system design. Cavestri[6] states bluntly that solution by dilution does not work.

Monochloramine exists mostly in the pool water. Trichloramine—because of its insolubility, volatility and vapor density—exists mostly in the air.[2] Medium-pressure UV systems help; they can be used to eliminate (some) monochloramine, dichloramine and (most) trichloramine in the recirculated water.[9] But a significant part of the trichloramine is in the air above the pool surface where it is untouched by the UV system. UV radiation can destroy trichloramine and some of its precursors, but cannot remove trichloramine once it is released to the air. The fact that trichloramine concentration in air does not correlate to combined chlorine concentration in water but does correlate to bather load, activity in water and ventilation rate,[3,10] indicates that UV water treatment alone cannot control the trichloramine problem.

Source Capture and Exhaust Strategy

Trichloramine does form in chlorinated nitrogen-contaminated pool water and there is no known technique of preventing it from forming (except to exclude swimmers from the pool). The only reasonable approach to improve indoor pool air quality is to remove trichloramine vapor from the surface of the water where it forms and initially accumulates, without distributing it throughout the natatorium in the process.

Based on the information presented in this article, a "source capture and exhaust" strategy outlined below and shown in *Figure 1* is recommended for improving indoor pool air quality:

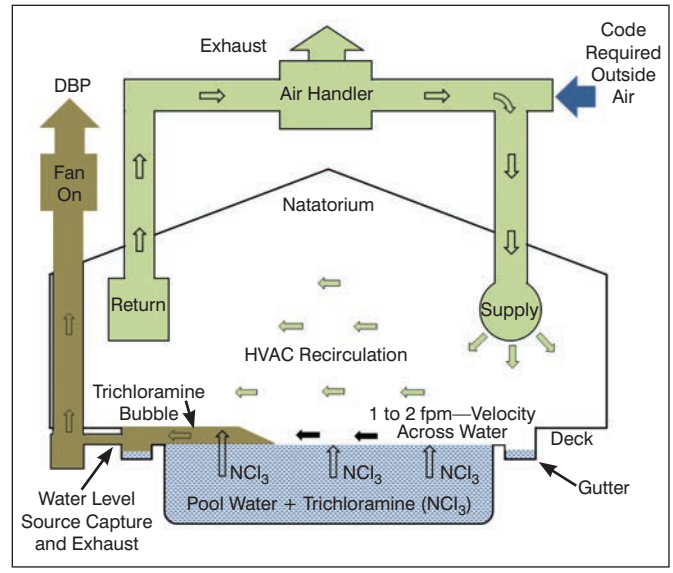

Figure 1: Source capture and exhaust strategy.

• Take advantage of the (high) density of trichloramine vapor to keep it separate from HVAC room air circulation.

• Exhaust trichloramine vapor to the outside from a level close to the waterline (the source of the trichloramine vapor) before it has a chance to diffuse into the natatorium space.

• Design the room air circulation system to set up a gentle air movement across the pool water surface that is complementary to the source capture exhaust flow.

• Allow fresh ventilation air to replace the trichloramine vapor.

Cavestri and Seeger-Clevenger[6] reported testing a setup similar to the source capture and exhaust strategy in a model pool using test vapors (trichloroethylene, perchloroethylene, chloroform and R-22) with known properties similar to those of trichloramine vapor. The model pool was contained in a controlled volume with a reconfigurable air recirculation system. Results showed that conventional top-level recirculation alone did not provide adequate dilution and clearance of the test vapor. The air system was reconfigured to add an air velocity component of 1 to 2 fpm (0.005 to 0.01 m/s) across the pool surface and a deck level exhaust to the outside; essentially complete elimination of the test vapors (trichloramine analogs) was achieved.

Water level exhaust is best for enhanced removal of trichloramine, especially in pools that have water levels significantly below deck level. The water line of the pool forms the base of the trichloramine bubble and a water level exhaust optimizes removal before the trichloramine vapor has a chance to diffuse into the natatorium. Without a water level exhaust all vapor must be lifted or displaced to exhaust or return height. The higher the exhaust or return, the more energy is required to lift or displace the vapor. With a water level exhaust it is only necessary to move the vapor cloud (bubble) slowly across the water surface to the exhaust openings. Systems must be sized for each application to remove trichloramine vapor from the

surface of the water before diffusion into the natatorium space can occur.

With the source capture and exhaust strategy, the HVAC system workload is reduced to providing the necessary air changes, ventilation air and dehumidification. If the HVAC system is sized in harmony with the low-level trichloramine vapor exhaust system, then the potential exists to reduce the total airflow requirements, thereby realizing further upfront and ongoing cost savings while improving the efficiency of trichloramine vapor removal.

Corrosion of building structure and equipment has always been a problem in indoor pool facilities. Source capture and exhaust of trichloramine vapor (and all other heavier-than-air DPBs) reduces the potential for corrosion, potentially reducing the need for expensive corrosion-resistant materials and coatings in natatoriums and equipment. Reducing the corrosion resistance requirement presents another potential for cost savings.

Conclusion

Trichloramine has been identified as the disinfectant by-product most likely to cause the adverse physiological responses associated with indoor swimming pool air.[2,4] It begins to cause eye discomfort and respiratory system symptoms at air concentrations around 0.50 mg/m^3; at concentrations of 0.70 mg/m^3 or greater most people experience symptoms.[2]

Research has shown that chemical reactions known to produce trichloramine in swimming pool water proceed to completion even under the conditions found in properly maintained swimming pools.[9,14]

High vapor density coupled with immiscibility and extreme volatility causes trichloramine vapor to initially accumulate in low-lying places above the pool water line making it difficult to remove with ordinary air circulation methods.[6]

Existing strategies to eliminate trichloramine vapor and improve indoor swimming pool air quality (solution by dilution and medium-pressure UV treatment of pool water) are not always effective.[3,10,15]

Source capture and exhaust of trichloramine vapor at water level is a strategy that takes advantage of physical and chemical characteristics to separate and remove a significant fraction of the trichloramine vapor from indoor swimming pool air[6] while potentially reducing building, equipment and operating cost. Source capture and exhaust, as presented in this article, is particularly suited for conventional recreational and competition pools. Indoor water parks and recreational pools with water features present unique challenges that also

can be met with creative application of the source capture concept, but are beyond the scope of this article.

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