

# Validation of Minimum Effective Free Chlorine to Cyanuric Acid Ratios in Recreational Water: Theoretical Analysis and Proposed Experimental Protocol

PoolFu Research

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## Abstract

*The recreational water industry has adopted specific minimum free chlorine to cyanuric acid (FC/CYA) ratios of 7.5% for manually-chlorinated pools and 4.5% for saltwater generator (SWG) pools as operational guidelines for adequate disinfection. These ratios originated from practitioner observation rather than controlled microbiological validation. This paper examines the theoretical foundation for these ratios by applying established equilibrium chemistry to calculate actual hypochlorous acid (HOCl) concentrations, then evaluating whether these concentrations satisfy pathogen inactivation requirements established by regulatory CT (concentration × time) standards. Analysis indicates the 7.5% ratio maintains approximately 0.03 mg/L HOCl at pH 7.5 and 25°C, providing CT values adequate for bacterial and viral inactivation under idealized conditions. However, real pools deviate substantially from idealized assumptions: hydraulic inefficiencies reduce effective contact time, bather load creates transient oxidant demand, and temperature and pH variations erode HOCl availability. The 4.5% SWG ratio lacks equivalent theoretical support, though continuous chlorine generation and high-concentration microenvironments at the electrode surface may provide compensatory benefits not captured by bulk chemistry analysis. Neither ratio provides meaningful protection against Giardia or Cryptosporidium at typical CYA levels. We propose a controlled experimental protocol to validate these ratios through direct measurement of pathogen inactivation kinetics across the practical CYA range of 30-100 mg/L.*

**Keywords:** cyanuric acid, hypochlorous acid, chlorine disinfection, swimming pool chemistry, CT value, pathogen inactivation

## 1. INTRODUCTION

Cyanuric acid (1,3,5-triazine-2,4,6-triol; CYA) has been employed as a chlorine stabilizer in outdoor swimming pools since the late 1950s [1]. The compound protects hypochlorous acid (HOCl) from ultraviolet photodegradation through reversible binding, forming chlorinated isocyanurates that function as a reservoir of available chlorine [2]. This stabilization extends chlorine persistence from approximately four hours in unstabilized water to multiple days, substantially reducing chemical costs and maintenance burden for outdoor pool operators.

However, this protective mechanism carries a significant tradeoff. The same equilibrium that shields chlorine from UV degradation also sequesters the active disinfectant species, reducing the instantaneous concentration of HOCl available for pathogen inactivation [3]. Research beginning in the 1960s demonstrated that CYA presence substantially increases the time required to achieve equivalent kill rates for bacteria, viruses, and protozoan parasites [4][5][6].

The pool service industry has responded to this challenge by adopting ratio-based chlorine targets. Rather than maintaining fixed free chlorine concentrations regardless of CYA level, practitioners have converged on minimum FC/CYA ratios: 7.5% for pools using manual chlorination and 4.5% for pools equipped with saltwater chlorine generators [7]. These ratios derive primarily from field observation of algae prevention efficacy rather than controlled microbiological studies [8].

Algae prevention represents a relatively low bar for disinfection capability since algae are visible, grow slowly, and provide operators feedback within days. Pathogen inactivation, particularly for organisms responsible for recreational water illness (RWI), requires more rigorous disinfection standards that may or may not coincide with the threshold for algae control.

This paper addresses four questions. First, can the 7.5% FC/CYA ratio be validated through first-principles chemistry, demonstrating that it maintains HOCl concentrations adequate for pathogen inactivation under typical pool conditions? Second, how do temperature and pH variations affect the

adequacy of this ratio? Third, how do real-world deviations from idealized assumptions (hydraulic inefficiency, bather load, combined chlorine formation) affect the practical safety margin? Fourth, what experimental protocol would be required to definitively validate or refine these ratios through controlled microbiological studies?

**Summary of findings:** The 7.5% ratio maintains HOCl concentrations theoretically adequate for bacterial and viral inactivation under favorable conditions ( $\text{pH} \leq 7.5$ , temperature  $\geq 25^\circ\text{C}$ ) with modest safety margin. The ratio is not adequate at elevated pH or reduced temperature without adjustment. The 4.5% SWG ratio lacks validated support. Neither ratio protects against protozoan parasites. The ratios likely succeed in residential pools because pathogen challenges are rare and the chlorinated cyanurate reservoir buffers against demand transients, not because the safety margins are generous.

## 2. THEORETICAL FRAMEWORK

### *2.1 Equilibrium Chemistry of the Chlorine-Cyanurate System*

The complete water chemistry model for aqueous solutions containing free chlorine and cyanuric acid was established by O'Brien and colleagues at Harvard University [9][10]. The system involves ten independent equilibrium reactions at  $25^\circ\text{C}$  and 0.020 M ionic strength, governing the distribution of chlorine among hypochlorous acid (HOCl), hypochlorite ion ( $\text{OCl}^-$ ), and six chlorinated cyanurate species ( $\text{Cl}_3\text{CY}$ ,  $\text{HCl}_2\text{CY}$ ,  $\text{Cl}_2\text{CY}^-$ ,  $\text{H}_2\text{ClCY}$ ,  $\text{HCICY}^-$ , and  $\text{ClCY}^{2-}$ ), in addition to four non-chlorinated isocyanurate species ( $\text{H}_3\text{CY}$ ,  $\text{H}_2\text{CY}^-$ ,  $\text{HCY}^{2-}$ , and  $\text{CY}^{3-}$ ).

The rapid equilibration between these species (demonstrated by Matte et al. to occur on timescales of seconds) [11] means that when chlorine is added to water containing CYA, the system reaches equilibrium essentially instantaneously. At this equilibrium, a substantial fraction of the total chlorine is bound to cyanurate species rather than existing as free chlorine.

Wahman and Alexander at the U.S. Environmental Protection Agency developed a simplified model applicable to drinking water and recreational water conditions ( $6.5 \leq \text{pH} \leq 9.5$ ,  $\text{TOTCl} \leq 10 \text{ mg Cl}_2/\text{L}$ , and  $\text{TOTCy} \leq 10 \text{ mg Cy}/\text{L}$  as cyanuric

acid) [12][13]. This "Simple Model" requires only four temperature-dependent equilibrium expressions and accounts for six chemical species: free chlorine (HOCl and OCl<sup>-</sup>), cyanuric acid and its first dissociation product (H<sub>3</sub>CY and H<sub>2</sub>CY<sup>-</sup>), and two dominant chlorinated cyanurates (HCICY<sup>-</sup> and Cl<sub>2</sub>CY<sup>-</sup>).

The key equilibrium constants at 25°C are:

**Table 1. Key Equilibrium Constants for the Chlorine-Cyanurate System at 25°C**

Reaction	Equilibrium Constant	Reference
$\text{HOCl} \rightleftharpoons \text{H}^+ + \text{OCl}^-$	$\text{pK}_a = 7.53$	Morris (1966) [14]
$\text{H}_3\text{CY} \rightleftharpoons \text{H}^+ + \text{H}_2\text{CY}^-$	$\text{pK}_6 = 6.88$	O'Brien et al. (1974) [10]
$\text{HCICY}^- \rightleftharpoons \text{HOCl} + \text{H}_2\text{CY}^-$	$\text{pK}_{7a} = 4.65$	Wahman & Alexander (2019) [13]
$\text{Cl}_2\text{CY}^- \rightleftharpoons \text{HOCl} + \text{HCICY}^-$	$\text{pK}_{9a} = 5.83$	Wahman & Alexander (2019) [13]

## 2.2 Calculating HOCl Concentration from Measured Free Chlorine

Standard pool water testing using DPD (N,N-diethyl-p-phenylenediamine) reagents cannot distinguish between free chlorine and chlorine bound to cyanurate species. The DPD method reacts directly with HOCl and, due to the rapid hydrolysis of chlorinated cyanurates releasing additional HOCl during the test, effectively measures total available chlorine (the sum of free chlorine and chlorine bound in the cyanurate reservoir) [15][16].

The consequence is that measured "free chlorine" values from DPD tests substantially overestimate actual free chlorine concentration when CYA is present. This measurement bias has been documented by multiple researchers and represents a fundamental limitation of routine pool water testing [17][18].

To calculate actual HOCl concentration from measured values, one must apply the equilibrium model. For typical pool conditions (pH 7.5, CYA substantially exceeding FC), approximately 97-99% of measured chlorine is bound to cyanurate species rather than existing as free HOCl or OCl<sup>-</sup>.

Using the Wahman equilibrium calculator or direct computation from the Simple Model equations, we can determine HOCl concentration as a function of measured FC (actually total chlorine), CYA, pH, and temperature [19].

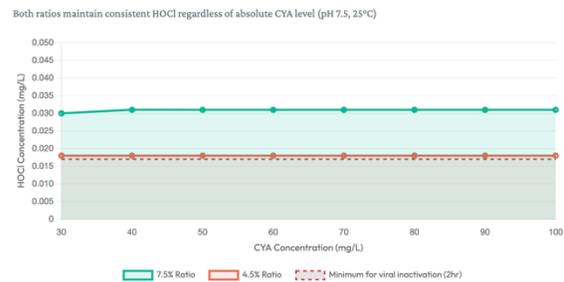
## 2.3 HOCl Concentrations at the 7.5% and 4.5% FC/CYA Ratios

Table 2 presents calculated HOCl concentrations for the 7.5% FC/CYA ratio across the practical CYA range, assuming pH 7.5 and 25°C.

**Table 2. Calculated HOCl Concentrations at 7.5% FC/CYA Ratio (pH 7.5, 25°C)**

CYA (mg/L)	FC at 7.5% (mg/L)	Calculated HOCl (mg/L)	HOCl as % of FC
30	2.25	0.030	1.3%
50	3.75	0.031	0.8%
70	5.25	0.031	0.6%
90	6.75	0.031	0.5%
100	7.50	0.031	0.4%

## HOCl Concentration Across CYA Range:



The ratio-based approach maintains remarkably consistent HOCl concentration (approximately 0.03 mg/L) across the CYA range. This is the chemical rationale for expressing minimum chlorine as a percentage of CYA rather than as a fixed concentration: the percentage compensates for CYA's sequestering effect.

Table 3 presents equivalent calculations for the 4.5% SWG ratio.

**Table 3. Calculated HOCl Concentrations at 4.5% FC/CYA Ratio (pH 7.5, 25°C)**

CYA (mg/L)	FC at 4.5% (mg/L)	Calculated HOCl (mg/L)	Ratio to 7.5%
30	1.35	0.017	0.56%
50	2.25	0.017	0.76%
70	3.15	0.017	0.54%
90	4.05	0.017	0.42%
100	4.50	0.017	0.38%

50	2.25	0.018	58%
70	3.15	0.018	58%
90	4.05	0.018	58%
100	4.50	0.018	58%

The 4.5% ratio provides approximately 58% of the HOCl concentration maintained by the 7.5% ratio at equivalent conditions, implying proportionally longer contact times for equivalent pathogen inactivation.

#### 2.4 The Reservoir Effect: Buffering Under Demand

The discussion thus far has framed CYA's chlorine sequestration as purely negative, reducing instantaneous disinfectant concentration. This framing is incomplete.

The chlorinated cyanurate reservoir provides demand buffering that unstabilized pools lack. When oxidant demand is introduced (bather contamination, organic debris, algae), the system responds differently depending on whether CYA is present:

**Unstabilized pool:** HOCl is consumed directly. Concentration drops sharply until the next chlorine dose. If demand exceeds available chlorine, disinfection fails until operator intervention.

**CYA-stabilized pool:** HOCl consumption shifts the chlorinated cyanurate equilibrium, releasing additional HOCl from the bound reservoir. The much larger pool of bound chlorine (typically 30-50x the free chlorine concentration) buffers the system against demand spikes. HOCl concentration drops less sharply and recovers continuously as the equilibrium re-establishes.

This buffering effect is part of why CYA-stabilized pools maintain more consistent disinfection under variable conditions than the instantaneous HOCl calculation might suggest. The reservoir acts as a chemical capacitor, smoothing out demand transients.

However, the buffering has limits. Sustained high demand will draw down the total available chlorine (bound + free), eventually depleting the reservoir. The equilibrium cannot create chlorine, only redistribute it. Under heavy bather load or after contamination events, measured "free chlorine" (total available

chlorine) will decline even as the system attempts to maintain HOCl through reservoir release.

### 3. DERIVING THE HOCL TARGET: WHY 0.03 MG/L?

#### 3.1 The Empirical Origin of the 7.5% Ratio

The 7.5% FC/CYA ratio emerged from practitioner observation rather than theoretical derivation. Pool service professionals, notably Ben Powell and contributors to online pool care communities, converged on this ratio through trial and error, primarily using algae control as the feedback signal [7][8]. Pools maintaining at least 7.5% FC/CYA resisted algae; those falling below experienced algae growth.

The equilibrium chemistry tells us this ratio maintains approximately 0.03 mg/L HOCl at pH 7.5 and 25°C. But this concentration was not derived from first principles. It is the HOCl concentration that corresponds to the empirically-successful ratio.

The question then becomes: does this empirically-derived concentration have independent theoretical support from disinfection science? If CT analysis confirms that 0.03 mg/L HOCl provides adequate pathogen inactivation, the practitioner-derived ratio gains scientific legitimacy. If not, either the ratio is inadequate for pathogen control (despite controlling algae) or the theoretical analysis is missing something.

#### 3.2 Derivation from CT Requirements

We can work backward from EPA CT requirements to determine the minimum HOCl concentration needed for pathogen inactivation within a specified contact time.

For 4-log virus inactivation at 25°C, the EPA specifies  $CT = 2 \text{ mg}\cdot\text{min}/\text{L}$  [21]. If we require this inactivation to occur within 2 hours (120 minutes), a reasonable expectation for a well-circulated pool:

$$C_{\text{min}} = CT / T = 2 / 120 = 0.017 \text{ mg/L HOCl}$$

For 99% (2-log) bacterial inactivation, published data suggest CT values on the order of 0.02-0.1  $\text{mg}\cdot\text{min}/\text{L}$  for vegetative bacteria [4][23]. At the conservative end, achieving this within 10 minutes requires:

$$C_{\text{min}} = 0.1 / 10 = 0.01 \text{ mg/L HOCl}$$

The 0.03 mg/L HOCl maintained by the 7.5% ratio provides approximately 1.8x the minimum for viral inactivation and 3x the minimum for rapid bacterial kill. This represents a modest safety factor, not a generous one.

### 3.3 The Safety Factor Question

A 1.8x safety factor over theoretical minimum would be adequate if pools behaved as ideal reactors with constant, uniform HOCl concentration. They do not. Section 5 will quantify several mechanisms that erode effective disinfection capacity:

- Hydraulic inefficiency reduces effective contact time to 40-60% of theoretical turnover
- Bather load creates transient HOCl demand that temporarily depresses disinfectant concentration
- Temperature and pH variations can reduce HOCl by 50-70% from baseline

These factors suggest the 1.8x safety factor at baseline conditions may be marginal when real-world deviations are considered. The 7.5% ratio likely succeeds in practice because (a) most residential pools operate under relatively favorable conditions much of the time, (b) the reservoir buffering effect partially compensates for demand transients, and (c) pathogen introduction events are relatively rare in residential settings.

## 4. TEMPERATURE AND PH EFFECTS ON HOCL AVAILABILITY

The baseline calculations in Sections 2 and 3 assume pH 7.5 and 25°C (77°F). Real pools operate across a range of conditions that significantly affect HOCl concentration.

### 4.1 The Combined Impact of pH and Temperature

Both pH and temperature independently affect the chlorine-cyanurate equilibrium, and their effects compound. Higher pH shifts the  $\text{HOCl} \rightleftharpoons \text{OCl}^-$  equilibrium toward the less biocidal hypochlorite ion. Lower temperature shifts the chlorinated cyanurate equilibria toward greater chlorine sequestration, releasing less HOCl from the CYA reservoir.

Table 4 presents calculated HOCl concentrations at the 7.5% ratio across the range of conditions encountered in residential pools.

**Table 4. HOCl Concentration (mg/L) at 7.5% FC/CYA Ratio Across Temperature and pH Range (50 mg/L CYA)**

	pH 7.2	pH 7.5	pH 7.8	pH 8.0
30°C (86°F)	0.048	0.036	0.023	0.016
25°C (77°F)	0.041	0.031	0.020	0.014
20°C (68°F)	0.034	0.025	0.016	0.011
15°C (59°F)	0.027	0.020	0.013	0.009

The variation is substantial. A pool at pH 7.2 and 86°F maintains 0.048 mg/L HOCl at the 7.5% ratio. The same ratio at pH 7.8 and 68°F provides only 0.016 mg/L HOCl, a 67% reduction. At pH 8.0 and 59°F, HOCl drops to 0.009 mg/L, less than one-third of the 0.03 mg/L baseline and below the theoretical minimum for viral inactivation within 2 hours.

### 4.2 Implications for Disinfection Capability

Section 3 established that 0.03 mg/L HOCl provides a 1.8x safety factor over the theoretical minimum for viral inactivation. Table 4 reveals that this threshold is met only in the upper-left portion of the matrix. At pH 7.8 or above, or at temperatures below 20°C, the 7.5% ratio falls below this already-modest target.

The situation is compounded by temperature effects on pathogen inactivation kinetics. Lower temperatures not only reduce HOCl concentration but also slow microbial kill rates. EPA CT requirements increase substantially at lower temperatures (see Section 6), meaning cooler pools face a double penalty: less disinfectant available and more disinfectant-time required.

### 4.3 Recommended Ratio Adjustments

To maintain equivalent disinfection capability across the operating range, Table 5 provides recommended minimum FC/CYA ratios adjusted for temperature and pH. These ratios are calculated to maintain approximately 0.03 mg/L HOCl under each condition.

**Table 5. Recommended Minimum FC/CYA Ratios to Maintain ~0.03 mg/L HOCl**

	pH 7.2	pH 7.5	pH 7.8	pH 8.0
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30°C (86°F)	5%	6.5%	10%	14%
25°C (77°F)	5.5%	7.5%	11%	16%
20°C (68°F)	6.5%	9%	14%	20%
15°C (59°F)	8%	11%	17%	25%

Several observations follow:

**The 7.5% ratio assumes tight pH control.** It provides adequate HOCl only at pH 7.5 or below when water is warm. Pools routinely operated at pH 7.6-7.8 require higher ratios.

**Cool pools need substantially more chlorine.** An unheated pool at 68°F and pH 7.5 should target 9% FC/CYA rather than 7.5% to achieve equivalent disinfection. Competition pools maintained at 77-82°F with pH 7.4-7.6 fare better.

**pH control is more effective than increasing chlorine.** Moving from pH 7.8 to pH 7.5 at 25°C allows a reduction from 11% to 7.5% FC/CYA while maintaining the same HOCl. Operators struggling to maintain high FC/CYA ratios should prioritize pH management.

#### *4.4 Conditions Incompatible with CYA-Stabilized Chlorination*

The extreme values in Table 5 reveal a practical limit. At pH 8.0 and 59°F, maintaining 0.03 mg/L HOCl would require a 25% FC/CYA ratio, meaning 12.5 mg/L FC at 50 mg/L CYA. This is operationally unrealistic and would create other problems (swimmer discomfort, equipment corrosion, chlorine odor from increased chloramine formation).

Some condition combinations are simply incompatible with CYA-stabilized chlorination at the CYA levels typically used (30-100 mg/L). Pools operating at pH above 7.8 with water temperatures below 65°F cannot achieve adequate disinfection through FC/CYA ratio management alone. These conditions require one of the following:

1. Aggressive pH reduction to below 7.6
2. CYA reduction below 30 mg/L (accepting higher chlorine consumption and UV degradation)

3. Transition to unstabilized chlorination with frequent dosing

4. Supplemental disinfection (UV, ozone) to compensate for inadequate chlorine efficacy

5. Acceptance that routine disinfection will be inadequate, with reliance on low bather load and response protocols

Indoor pools, particularly those in cooler climates maintaining lower water temperatures for athletic use, may find that CYA stabilization is inappropriate for their application.

## **5. REAL-WORLD DEVIATIONS FROM IDEALIZED ASSUMPTIONS**

The CT calculations in this analysis assume constant HOCl exposure throughout the contact time, uniform mixing, and no competing oxidant demand. Real pools deviate substantially from these assumptions. This section quantifies the impact of these deviations.

### *5.1 Hydraulic Inefficiency*

Swimming pools are not continuous stirred-tank reactors (CSTRs). They are complex hydraulic systems with inlets (return jets), outlets (skimmers, main drains), and varying geometry. Water movement is non-uniform, creating dead zones, short-circuiting, and stratification.

Tracer studies and computational fluid dynamics (CFD) modeling of pool hydraulics indicate that effective contact time is typically 40-60% of theoretical turnover time [32][33]. A pool with 6-hour turnover provides not 360 minutes of contact time but 144-216 minutes of effective contact time due to these inefficiencies.

The implications for disinfection are significant. If viral 4-log inactivation requires 100 minutes at 0.03 mg/L HOCl (Section 3), hydraulic inefficiency means the pool must provide 167-250 minutes of theoretical contact time for equivalent real-world inactivation. A single turnover cycle may be insufficient.

For Giardia, where calculated contact times already exceed 24 hours (Section 6), hydraulic inefficiency extends effective inactivation time to 40-60 hours. The margin between "inadequate" and "completely inadequate" may seem academic, but it affects how we communicate risk to operators.

## 5.2 Spatial Heterogeneity

Related to hydraulic inefficiency is spatial variation in water chemistry. HOCl concentration is not uniform throughout the pool volume:

- Water near return jets has recently passed through the circulation system and any inline chlorinator; it may have higher chlorine than bulk pool water.
- Water in corners, behind ladders, in steps, and in other areas with poor circulation may have lower effective chlorine due to localized demand and poor mixing.
- Surface water receives direct UV exposure (in outdoor pools) and experiences faster chlorine degradation than deeper water.
- Water near bathers experiences localized demand from sweat, urine, and organic matter.

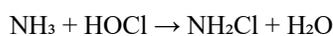
A pathogen's fate depends on where it is introduced and how it moves through the pool. A virus introduced near a return jet experiences different chlorine exposure than one introduced in a dead zone corner. The "average" CT calculated from bulk pool chemistry may not represent the exposure experienced by any particular pathogen.

## 5.3 Bather Load and Transient Demand

Swimmers introduce oxidant demand through multiple mechanisms:

- **Ammonia and organic nitrogen** from sweat and urine react with HOCl to form chloramines (combined chlorine)
- **Organic matter** (skin cells, cosmetics, sunscreen, body oils) consumes HOCl through oxidation
- **Fecal contamination** introduces both pathogens and organic demand simultaneously

The chloramine formation kinetics deserve particular attention. At pH 7.5 and the ammonia concentrations typical of occupied pools (0.1-0.5 mg/L NH<sub>3</sub>-N from sweat and urine), monochloramine formation is rapid [34]. The reaction:



proceeds with a rate constant of approximately  $4 \times 10^6 \text{ M}^{-1}\text{s}^{-1}$  at pH 7.5 [35]. At 0.03 mg/L HOCl ( $4 \times 10^{-7} \text{ M}$ ) and 0.3 mg/L NH<sub>3</sub>-N ( $2 \times 10^{-5} \text{ M}$ ), the half-

life of HOCl with respect to chloramine formation is on the order of seconds.

The chlorinated cyanurate reservoir responds to this demand. As HOCl is consumed, the equilibrium shifts to release more HOCl from bound chlorine. Matte et al. demonstrated that this equilibration occurs within seconds [11]. The reservoir buffers the HOCl concentration, preventing the sharp drops that would occur in unstabilized water.

However, the buffering is not instantaneous and not unlimited. During periods of high bather load:

1. HOCl experiences transient depression as demand temporarily exceeds reservoir release rate
2. Total available chlorine (measured FC) declines as chlorine is consumed
3. If demand is sustained, the reservoir depletes and HOCl drops proportionally

The practical implication is that pools at the minimum FC/CYA ratio have reduced safety margin during heavy use. The 7.5% ratio may provide adequate disinfection for a lightly-used residential pool but become marginal during a pool party. Practitioners intuitively recognize this, targeting higher FC before anticipated heavy use.

## 5.4 Combined Chlorine Interference

The formation of chloramines (combined chlorine) from the reaction of HOCl with nitrogenous compounds has implications beyond simple oxidant demand. Chloramines are themselves disinfectants, but with substantially lower efficacy than HOCl. Monochloramine has approximately 1/100th the bactericidal activity of HOCl; dichloramine and trichloramine are more effective but still inferior to HOCl and create other problems (irritation, off-gassing) [36].

In a pool with significant combined chlorine, the total disinfection capacity is not simply the HOCl concentration but a weighted sum of HOCl and chloramine contributions. However, at the low HOCl concentrations present in CYA-stabilized pools (0.02-0.05 mg/L), even modest chloramine levels can represent a significant fraction of total oxidizing capacity.

This creates an analytical complication. DPD tests measure total chlorine (free + combined) in unstabilized water, but in CYA-stabilized water, DPD measures total available chlorine (free + cyanurate-bound) while combined chlorine requires a separate measurement. The practical disinfection capacity of a CYA-stabilized pool with bather load depends on:

- HOCl concentration (calculated from equilibrium)
- Chloramine concentration (measured or estimated from bather load)
- The relative efficacy of each species against target organisms

This analysis has focused on HOCl, but a complete treatment would incorporate chloramine contributions, particularly under heavy bather load conditions.

### 5.5 Implications for Safety Factors

The deviations described above collectively suggest that the 1.8x safety factor provided by the 7.5% ratio at baseline conditions is probably inadequate when real-world factors are considered. Hydraulic inefficiency alone may require doubling calculated contact times. Bather load creates transient HOCl depression. Spatial heterogeneity means some pool volumes receive less than average CT.

How much these factors matter in combination is not well characterized. No published studies quantify the aggregate real-world correction factor for pool disinfection. A reasonable guess might be 2-3x, but this is speculation informed by the hydraulic literature rather than direct measurement.

This uncertainty cuts both ways. The 7.5% ratio may be marginal under real conditions, or the theoretical framework may be missing compensatory factors (like the reservoir buffering effect discussed in Section 2.4) that make the ratio more robust than bulk chemistry suggests. The honest answer is that we do not know with precision.

## 6. PATHOGEN INACTIVATION REQUIREMENTS

### 6.1 The CT Concept

Disinfection efficacy is quantified using the CT concept, where C represents disinfectant concentration

(mg/L) and T represents contact time (minutes). The CT value required for a specified log reduction of a target organism depends on the disinfectant, temperature, pH, and organism resistance [20].

The U.S. Environmental Protection Agency's Surface Water Treatment Rule (SWTR) established CT requirements for drinking water disinfection, specifying values for inactivation of *Giardia lamblia* cysts and enteric viruses using free chlorine, chlorine dioxide, ozone, and chloramines [21]. These tables assume disinfection with free chlorine in the absence of CYA; the CT values reference actual HOCl + OCl<sup>-</sup> concentration, not the "total available chlorine" measured by DPD tests in stabilized water.

### 6.2 Bacterial Inactivation

Anderson's foundational 1965 study examined the influence of CYA on chlorine's bactericidal effectiveness against *Streptococcus faecalis* (now classified as *Enterococcus faecalis*) [4]. At 0.5 mg/L total chlorine and pH 7.0, the time required for 99% kill increased from less than 15 seconds without CYA to approximately 12 minutes at 100 mg/L CYA.

Wojtowicz reanalyzed Anderson's data, plotting kill time against calculated HOCl concentration rather than measured total chlorine [23]. This analysis demonstrated a clear linear relationship between HOCl concentration and kill time, confirming HOCl as the active bactericidal species. The apparent "chlorine lock" effect of CYA disappears when expressed in terms of actual HOCl: CYA does not inhibit chlorine's bactericidal activity, it simply reduces the instantaneous HOCl concentration available.

At 0.03 mg/L HOCl, extrapolation from these data suggests bacterial kill times on the order of 5-30 minutes for vegetative bacteria under ideal conditions. Applying the 2-3x real-world correction factor from Section 5.5 suggests 10-90 minutes under actual pool conditions.

### 6.3 Viral Inactivation

The EPA CT tables for 4-log (99.99%) virus inactivation with free chlorine at pH 6-9 provide reference values [21]:

**Table 6. EPA CT Requirements for 4-Log Virus Inactivation with Free Chlorine**

Temperature	CT Required (mg·min/L)
10°C (50°F)	6
15°C (59°F)	4
20°C (68°F)	3
25°C (77°F)	2

At 0.03 mg/L HOCl and 25°C, the theoretical time to achieve CT = 2 is:

$$T = CT / C = 2 / 0.03 = 67 \text{ minutes}$$

Applying the 2-3× real-world correction: 130-200 minutes for 4-log viral inactivation under actual pool conditions.

For cooler conditions (20°C), achieving CT = 3 requires:

$$T_{\text{theoretical}} = 3 / 0.03 = 100 \text{ minutes}$$

$$T_{\text{real-world}} = 200\text{-}300 \text{ minutes}$$

A well-circulated pool with 6-8 hour turnover can achieve these contact times within 1-2 turnovers, provided the pool maintains the 7.5% ratio at baseline pH and temperature. The margin becomes tighter at elevated pH or reduced temperature.

#### 6.4 Giardia: The Ratio Does Not Protect

EPA CT requirements for 3-log (99.9%) *Giardia lamblia* cyst inactivation are substantially higher than for viruses [21]:

**Table 7. EPA CT Requirements for 3-Log Giardia Inactivation with Free Chlorine (pH 7.5, ≤0.4 mg/L)**

Temperature	CT Required (mg·min/L)
10°C (50°F)	125
15°C (59°F)	83
20°C (68°F)	62
25°C (77°F)	42

At 0.03 mg/L HOCl and 25°C:

$$T_{\text{theoretical}} = 42 / 0.03 = 1,400 \text{ minutes} \approx 23 \text{ hours}$$

$$T_{\text{real-world}} = 2,800\text{-}4,200 \text{ minutes} \approx 2\text{-}3 \text{ days}$$

At 20°C:

$$T_{\text{theoretical}} = 62 / 0.03 = 2,067 \text{ minutes} \approx 34 \text{ hours}$$

$$T_{\text{real-world}} = 4,100\text{-}6,200 \text{ minutes} \approx 3\text{-}4 \text{ days}$$

The 7.5% FC/CYA ratio does not provide Giardia inactivation under any realistic interpretation.

**The 7.5% ratio is not a Giardia-protective standard.** If a fecally-contaminated bather introduces Giardia cysts to a pool operating at the 7.5% ratio, chlorine will not inactivate those cysts within the same day or the next. Complete inactivation under real-world conditions requires multiple days of continuous exposure at maintained HOCl, which is unlikely given overnight chlorine decline, bather load variation, and other factors.

Residential pools operating at the 7.5% ratio rely on prevention (bather hygiene, excluding ill swimmers), physical removal (filtration), and response protocols (closure, shock treatment) rather than routine disinfection for Giardia control. The ratio is validated for bacterial and viral protection only. For protozoan parasites, pool operators should understand that chlorine at the minimum ratio provides no meaningful protection.

#### 6.5 Cryptosporidium: Chlorine Does Not Work

*Cryptosporidium parvum* presents unique challenges for chlorine disinfection due to the organism's extreme tolerance to oxidizing disinfectants. CDC recommendations for Cryptosporidium remediation specify CT values of 15,300 mg·min/L for 3-log inactivation in the absence of CYA [26].

Murphy et al. (2015) at CDC directly investigated CYA's impact on Cryptosporidium inactivation under hyperchlorination conditions [27]. Their findings demonstrated that CYA presence substantially delays chlorine inactivation of Cryptosporidium oocysts:

- At 20 mg/L free chlorine with no CYA: 3-log inactivation achieved at CT ≈ 15,300 mg·min/L
- At 20 mg/L free chlorine with 8 mg/L CYA: 3-log CT ≈ 17,800 mg·min/L
- At 20 mg/L free chlorine with 16 mg/L CYA: 3-log CT ≈ 31,500 mg·min/L
- At 20 mg/L free chlorine with 48 mg/L CYA: Only 1-log CT achievable (76,500 mg·min/L)

- At 20 mg/L free chlorine with ~100 mg/L CYA: <1 log reduction after 72 hours

These results demonstrate that *Cryptosporidium* inactivation becomes practically impossible at CYA concentrations exceeding 15-50 mg/L, regardless of chlorine level. The CDC's MAHC now recommends that pools responding to diarrheal incidents reduce CYA to  $\leq 15$  mg/L before hyperchlorination, or employ supplemental disinfection (UV, ozone) capable of inactivating *Cryptosporidium* [29].

For routine pool operation, the FC/CYA ratio is irrelevant to *Cryptosporidium* protection at typical stabilizer levels (30-100 mg/L). Residential pools maintaining CYA in this range rely entirely on prevention (bather hygiene, excluding ill swimmers) and response (closure, draining, UV/ozone treatment) rather than chlorine disinfection for *Cryptosporidium* control.

## 7. THE 4.5% SWG RATIO: ANALYSIS AND ALTERNATIVE HYPOTHESES

### 7.1 Chemical Analysis

The 4.5% minimum ratio for saltwater generator pools provides approximately 58% of the HOCl concentration maintained by the 7.5% ratio at equivalent conditions. This translates to proportionally longer contact times for equivalent pathogen inactivation:

- Viral 4-log inactivation at 25°C theoretical: 111 minutes (vs. 67 minutes at 7.5%)
- Viral 4-log inactivation at 25°C real-world: 220-330 minutes (vs. 130-200 minutes at 7.5%)

No chemical property of electrolytically-generated chlorine differs from chlorine produced by other means. Sodium hypochlorite generated by saltwater electrolysis is chemically identical to sodium hypochlorite from other sources. The equilibrium distribution between HOCl, OCl<sup>-</sup>, and chlorinated cyanurates depends only on pH, temperature, and the concentrations of chlorine and cyanuric acid, not on the chlorine source.

### 7.2 Hypothesis 1: Continuous Generation and Reduced FC Variation

One proposed explanation for the apparent efficacy of the 4.5% ratio involves chlorine delivery dynamics rather than equilibrium chemistry.

Manually-chlorinated pools experience significant FC variation between dosing events. A pool dosed to 6 mg/L FC immediately after chlorine addition may decline to 2 mg/L FC over the following 24-48 hours before the next dose. This creates troughs where instantaneous disinfection capability is temporarily compromised.

SWG pools generate chlorine continuously during pump operation (typically 8-12 hours daily). This eliminates or substantially reduces FC variation. A SWG pool maintaining a steady 3.15 mg/L FC at 70 mg/L CYA provides consistent 0.018 mg/L HOCl throughout operation.

If pathogen inactivation follows first-order kinetics (astypically assumed), the integrated CT exposure over time may be equivalent or superior for SWG pools despite lower instantaneous HOCl, provided the manually-dosed pool experiences significant troughs.

### Limitations of this hypothesis:

1. SWG operation is not truly continuous. Most residential systems operate only during pump run time, typically 8-12 hours per day.
2. No controlled studies compare pathogen survival between continuously-chlorinated and manually-dosed pools at equivalent average chemistry.
3. The hypothesis depends on significant FC variation in manually-dosed pools, which well-maintained pools may not experience.

### 7.3 Hypothesis 2: Electrode Microenvironment Effect

A less-discussed mechanism involves the high local chlorine concentration at the electrode surface during electrolysis.

During SWG operation, the electrode surface experiences extremely high chlorine concentration in the boundary layer, potentially hundreds of mg/L. Any pathogen passing through the electrolytic cell receives brief but intense chlorine exposure independent of bulk pool concentration.

For a typical residential SWG producing 1-2 lb chlorine per day in a 20,000 gallon pool with 8-hour pump runtime and 50 GPM flow rate:

- Approximately 3 pool volumes pass through the cell per day
- Residence time in the cell is a few seconds
- Local chlorine concentration may exceed 100 mg/L

The CT experienced in the cell microenvironment, even over a few seconds at 100+ mg/L, could contribute meaningful pathogen inactivation. Over the course of a day, each pathogen would have multiple opportunities to pass through this high-concentration zone.

### Chlorine Delivery Patterns:



### Limitations of this hypothesis:

1. The actual chlorine concentration in the electrode boundary layer during residential SWG operation is not well-characterized.
2. Cell residence time is very short (seconds), limiting CT accumulation per pass.
3. No experimental validation of enhanced pathogen inactivation in SWG systems independent of bulk chemistry.

### 7.4 The Most Likely Explanation: We Haven't Measured the Right Outcome

The simplest explanation for why the 4.5% ratio appears to work is that we lack good feedback on whether it actually works for pathogen control.

Algae are visible. They grow within days of inadequate disinfection. An operator who experiences algae at the 4.5% ratio increases chlorine or troubleshoots. The feedback loop is tight.

Pathogens are invisible. Recreational water illness may not be connected to pool chemistry by the

affected swimmer. Symptoms appear days later, may be attributed to other causes, and often go unreported. A pool that inadequately controls pathogens looks identical to one that controls them well.

The apparent success of the 4.5% ratio may reflect inadequate outcome measurement rather than genuine equivalence to higher ratios. Until someone conducts controlled inactivation studies at these HOCl concentrations, we cannot distinguish between "4.5% works" and "4.5% fails in ways we don't detect."

This should be stated plainly: the 4.5% ratio is unvalidated. Pool operators using it are participating in an uncontrolled experiment.

### 7.5 The 4.5% Ratio Fails Under Common Conditions

Even if some unvalidated mechanism makes 4.5% adequate at baseline conditions, the ratio fails under conditions that many pools regularly experience.

**Table 8. HOCl Concentration (mg/L) at 4.5% FC/CYA Ratio Across Temperature and pH Range (50 mg/L CYA)**

	pH 7.2	pH 7.5	pH 7.8	pH 8.0
30°C (86°F)	0.029	0.022	0.014	0.010
25°C (77°F)	0.025	0.018	0.012	0.008
20°C (68°F)	0.020	0.015	0.010	0.007
15°C (59°F)	0.016	0.012	0.008	0.005

At pH 7.8 and 68°F, the 4.5% ratio provides only 0.010 mg/L HOCl, below the 0.017 mg/L theoretical minimum for viral inactivation within 2 hours. At these conditions, the 4.5% ratio is demonstrably inadequate by any theoretical standard.

SWG pools tend to drift toward higher pH due to the hydroxide ions produced during electrolysis. This makes SWG pools particularly susceptible to the pH-related erosion of disinfection capacity. SWG operators should not rely on the 4.5% ratio unless maintaining tight pH control (7.2-7.5).

### 7.6 Recommendation

The 4.5% ratio should be considered provisional guidance, not validated science. Pool operators who choose this ratio should understand they are accepting:

1. Reduced instantaneous HOCl compared to the 7.5% ratio
2. Reliance on unvalidated compensatory mechanisms (continuous generation, electrode microenvironment)
3. Clear inadequacy under non-ideal temperature and pH conditions
4. No additional protection against protozoan parasites (which neither ratio provides)

The conservative recommendation is that SWG operators target the 7.5% ratio as a general minimum, reserving the 4.5% ratio for pools demonstrating consistent pH control (7.2-7.5) and temperatures above 77°F.

## 8. WHAT VALIDATION WOULD REQUIRE

### 8.1 The Core Question

Does HOCl concentration alone predict pathogen inactivation in CYA-stabilized water, or do other factors (chlorinated cyanurate species, reservoir dynamics, chlorine source) matter?

If HOCl is the sole determinant, then the equilibrium calculations in this paper provide the complete picture, and the ratio-based approach is validated. If other factors matter, the ratios may need adjustment.

### 8.2 Why This Is Difficult

The organisms that matter most are the hardest to work with. *Giardia* requires specialized culture techniques. *Cryptosporidium* inactivation must be measured by cell culture infectivity rather than simple enumeration, since oocysts remain intact long after they lose the ability to infect.

Most published chlorine inactivation studies used free chlorine concentrations of 0.5-2.0 mg/L. The HOCl concentrations in CYA-stabilized pools (0.02-0.05 mg/L) are 10-100x lower. Extrapolating kill kinetics across this range introduces uncertainty that only direct measurement can resolve.

A meaningful study would need to test bacteria (*Enterococcus*, *Pseudomonas*), viruses (MS2 coliphage as surrogate), and ideally *Giardia* across the

CYA range of 30-100 mg/L, at multiple pH and temperature combinations. The protozoan work would require collaboration with CDC or similar specialized facilities.

### 8.3 What We Would Learn

If kill times at constant calculated HOCl are independent of total chlorine and CYA concentration, the ratio-based approach is validated. If kill times vary with CYA even at matched HOCl, something else is happening that this analysis does not capture.

The most policy-relevant finding would be identifying the temperature and pH boundaries where the 7.5% ratio becomes inadequate. Table 5 provides calculated estimates. Experimental confirmation would convert those estimates into defensible recommendations.

## 9. DISCUSSION

### 9.1 What the 7.5% Ratio Is and Isn't

The 7.5% FC/CYA ratio:

#### What it is:

- An empirically-derived guideline that maintains approximately 0.03 mg/L HOCl at pH 7.5 and 25°C
- Theoretically adequate for bacterial and viral inactivation under ideal conditions with modest safety margin
- Appropriate for residential pools operating at pH 7.2-7.6 and temperatures above 72°F
- A reasonable minimum for lightly-used pools in favorable conditions

#### What it isn't:

- A rigorously-validated microbiological standard
- Adequate under all conditions (fails at elevated pH, low temperature, or both)
- Protective against *Giardia* or *Cryptosporidium*
- A generous safety margin when real-world deviations from ideal conditions are considered

### 9.2 The Practical Success of an Imperfect Standard

The ratio works in practice despite marginal theoretical support. The reasons probably matter more than the chemistry:

**1. Most residential pools operate under favorable conditions much of the time.** Warm water, controlled pH, low bather load, and limited UV exposure (during evening/night hours) create conditions where the ratio provides adequate disinfection.

**2. The cyanurate reservoir provides demand buffering.** Transient HOCl consumption is partially compensated by equilibrium release from bound chlorine, smoothing out demand spikes that would cause more severe HOCl depression in unstabilized pools.

**3. Pathogen introduction events are rare in residential settings.** Most residential pools are not high-risk environments for RWI transmission. Low bather density, limited introduction of contamination, and small user groups mean the disinfection system is rarely challenged by significant pathogen loads.

**4. Operators often exceed the minimum.** The 7.5% ratio is a minimum, not a target. Many operators maintain higher ratios, particularly during heavy use or after anticipated contamination.

**5. Feedback mechanisms exist for some failures.** Algae growth provides visible feedback when disinfection is inadequate. While this doesn't detect pathogen failures directly, it correlates loosely with overall oxidant availability.

### *9.3 Limitations of the Current Analysis*

This analysis relies on equilibrium calculations and published CT values rather than direct experimental measurement. Several assumptions may not hold:

**1. CT model limitations.** The CT concept assumes first-order kinetics and constant disinfectant concentration. Real systems experience variable exposure, and inactivation kinetics may deviate from first-order at low concentrations.

**2. Limited data at low HOCl.** Most published inactivation studies were conducted at higher chlorine concentrations than those present in CYA-stabilized pools. Extrapolation to 0.02-0.05 mg/L HOCl introduces uncertainty.

**3. Organism variability.** CT requirements vary across strains, growth conditions, and environmental adaptation. The EPA values are conservative estimates, not precise thresholds.

**4. Real-world complexity not captured.** Biofilms, turbidity, suspended solids, and other factors affecting disinfectant access to pathogens are not addressed in the idealized analysis.

### *9.4 Implications for Industry Standards*

Current industry guidance presents the 7.5% and 4.5% ratios as simple minimums without temperature or pH qualification. The analysis here suggests these ratios should be understood as condition-specific:

**1. The 7.5% ratio is a minimum for pH 7.5 and 25°C only.** Guidance should include adjustment factors for non-ideal conditions, per Table 5.

**2. The 4.5% SWG ratio lacks validated support.** It should be presented as provisional pending experimental confirmation, with recommendation to target 7.5% under non-ideal conditions.

**3. Neither ratio provides meaningful protection against Giardia or Cryptosporidium at typical CYA levels.** The ratios likely succeed in practice not because of generous safety margins but because residential pools rarely face significant pathogen challenges, and the chlorinated cyanurate reservoir buffers against demand spikes. Controlled validation remains needed.

**4. Some conditions are incompatible with CYA-stabilized chlorination.** Pools operating at pH >7.8 or temperatures <65°F may be unable to achieve adequate disinfection at practical FC/CYA ratios and should consider alternative approaches.

## 10. CONCLUSIONS

**1. The 7.5% FC/CYA ratio has qualified theoretical support.** Equilibrium chemistry calculations confirm that this ratio maintains HOCl concentrations adequate for bacterial and viral inactivation at pH 7.5 and 25°C. The ratio represents an empirically-derived guideline that, upon analysis, turns out to have scientific justification under its assumed conditions.

**2. The ratio provides modest safety margin that erodes under non-ideal conditions.** The ~1.8× safety factor over theoretical minimum becomes inadequate when pH exceeds 7.6, temperature drops below 72°F, or real-world hydraulic and demand factors are considered. Operators should increase target ratios under these conditions per Table 5.

**3. The 4.5% SWG ratio lacks equivalent support.** While continuous chlorine generation and electrode microenvironment effects may provide compensatory benefits, no controlled research validates that the lower instantaneous HOCl concentration provides equivalent pathogen inactivation.

**4. Neither ratio protects against Giardia.** Contact times of 2-4 days for 3-log cyst inactivation under real-world conditions mean the 7.5% ratio should not be considered Giardia-protective. Pool operators rely on prevention and response protocols rather than routine disinfection.

**5. Cryptosporidium protection requires supplemental measures.** Neither ratio provides

meaningful Cryptosporidium inactivation at typical CYA levels. Pools relying solely on chlorine disinfection should understand they are accepting Cryptosporidium risk.

**6. The cyanurate reservoir provides demand buffering that partially compensates for low instantaneous HOCl.** This buffering effect, combined with the favorable conditions typical of residential pools, likely explains why the empirically-derived ratios succeed in practice despite marginal theoretical safety factors.

**7. Controlled experimental validation is needed.** The proposed phased protocol would definitively validate or refine these ratios, identify the temperature/pH boundaries of their adequacy, and test the hypotheses regarding SWG-specific mechanisms.

**8. Some operating conditions are incompatible with CYA-stabilized chlorination.** Pools at high pH, low temperature, or both cannot achieve adequate disinfection at practical FC/CYA ratios and require alternative approaches (pH control, CYA reduction, supplemental disinfection, or acceptance of reduced protection).

## CONFLICTS OF INTEREST

This research was conducted by PoolFu, which develops pool water chemistry software. The analysis was undertaken to inform product development and industry best practices.

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