TCEQ Directed Assistance Module (DAM) No. 5: Understanding and Controlling the Chloramination Process

Presented at the

West Harris County Regional Water Authority

***Chloramines 101* Workshop**

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by

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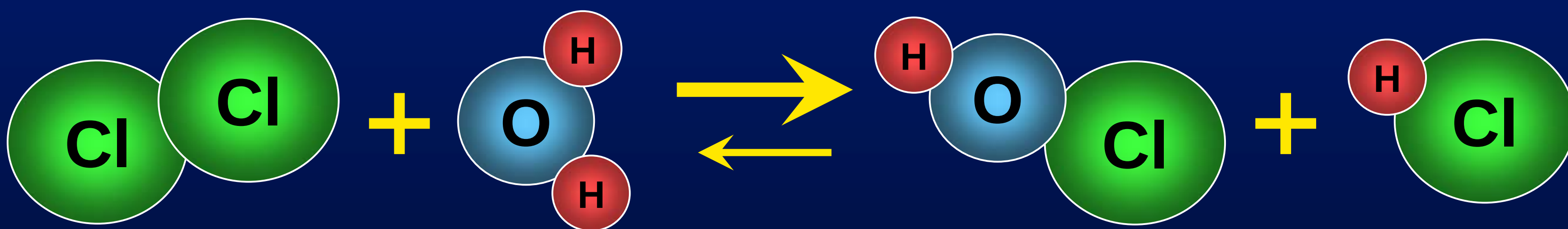
What will we cover during this Seminar?

- Basic chloramination chemistry
- The chlorine breakpoint curve
- Weight-based doses and feed rates
- Process control and monitoring
- The TCEQ’s regulatory approach
- DAM5 operator training

Basic Chloramination Chemistry

Chlorine (gas) Hydrolysis

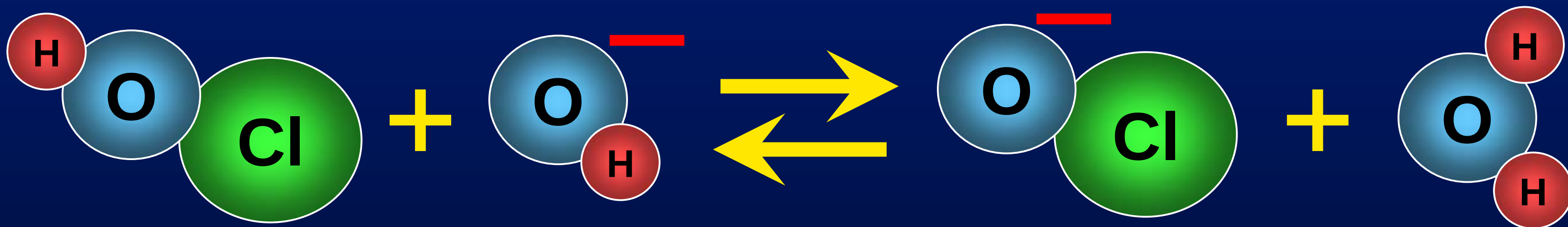
$$Cl_2 + H_2O \rightleftharpoons HOCl + HCl$$



Chlorine + Water $\rightleftharpoons$ Hypochlorous Acid + Hydrochloric Acid

Dissociation of Hypochlorous Acid

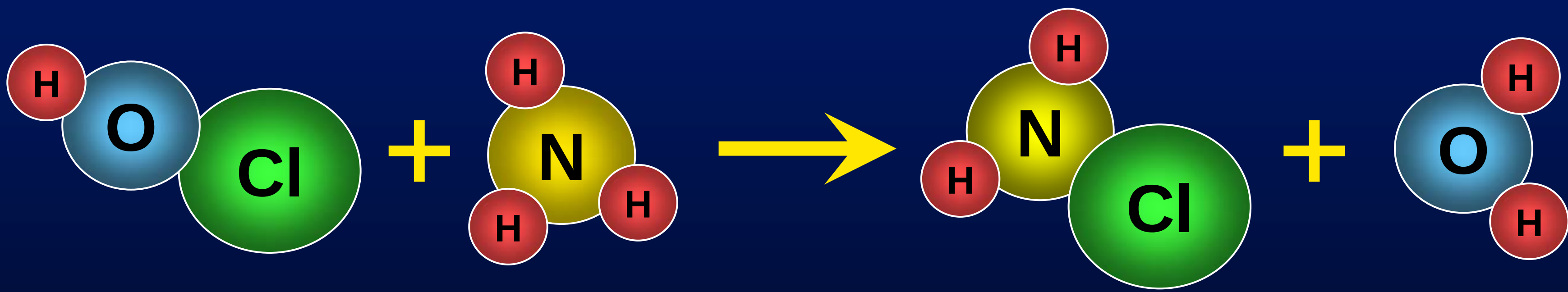
$$HOCl + OH^{-} \rightleftharpoons OCl^{-} + H_2O$$



Hypochlorous Acid + Hydroxide Ion ⇌ Hypochlorite Ion + Water

Monochloramine Formation

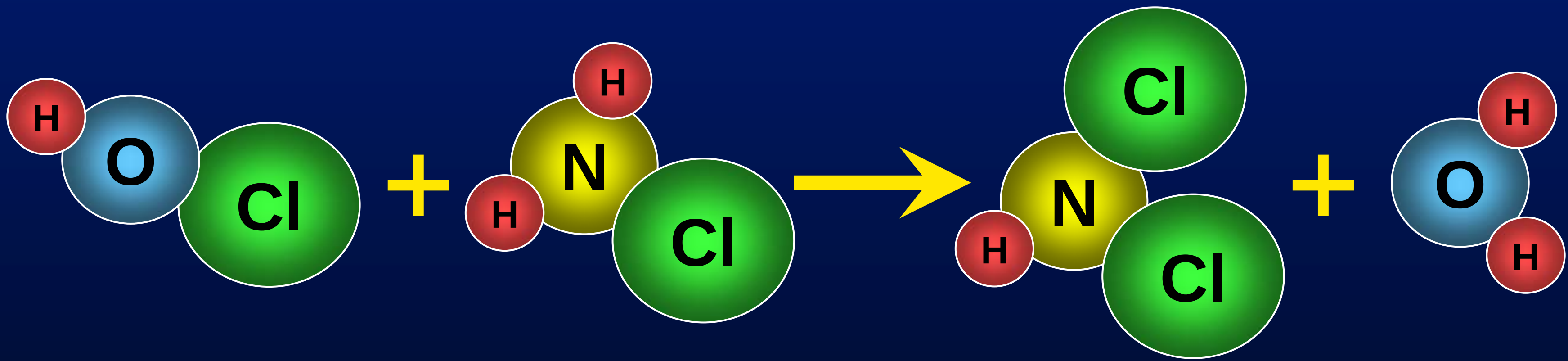
$$HOCl + NH_3 \longrightarrow NH_2Cl + H_2O$$



Hypochlorous Acid + Ammonia ⟶ Monochloramine + Water

Dichloramine Formation

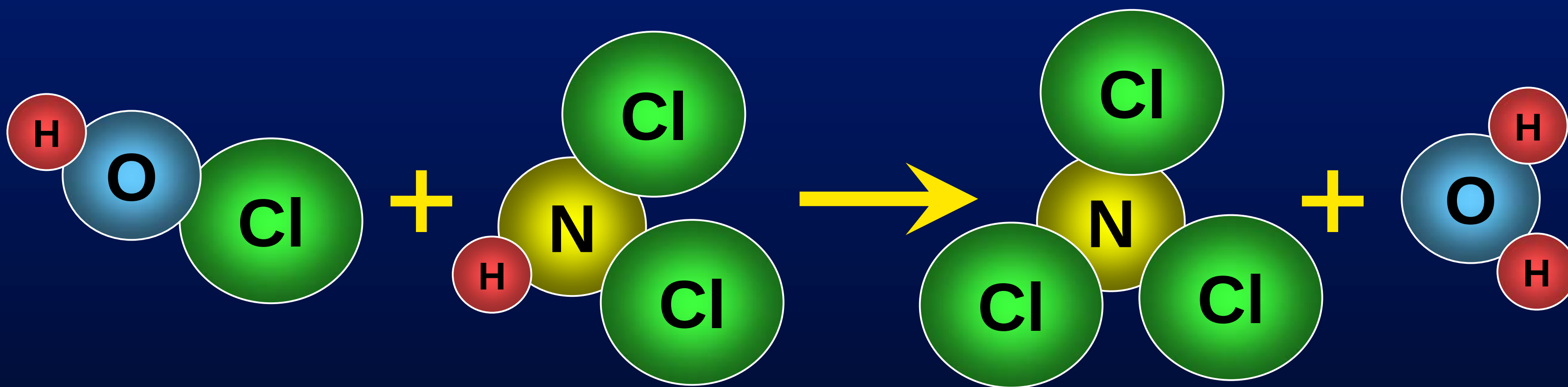
$$HOCl + NH_2Cl \longrightarrow NHCl_2 + H_2O$$



Hypochlorous Acid + Monochloramine ⟶ Dichloramine + Water

Trichloramine Formation

$$HOCl + NHCl_2 \longrightarrow NCl_3 + H_2O$$



Hypochlorous Acid + Dichloramine → Trichloramine + Water

Weight-Based Units of Measurement

Atom	Atomic Weight	Atom	Molecular Weight
Chlorine	35.5	Chlorine (Cl_2)	71
Nitrogen	14	Ammonia (NH_3)	17
Hydrogen	1	Monochloramine (NH_2Cl)	51
		Dichloramine ($NHCl_2$)	85
		Trichloramine ($NHCl_3$)	129

Weight-Based Ratios

(in the imaginary world)

$$\frac{1\ \text{mol}\ Cl_2}{1\ \text{mol}\ NH_3} \times \frac{71\ \text{lb}\ Cl_2}{1\ \text{mol}\ Cl_2} \times \frac{1\ \text{mol}\ NH_3}{17\ \text{lb}\ NH_3} = \frac{71\ \text{lb}\ Cl_2}{17\ \text{lb}\ NH_3}$$

$$= \frac{4.2\ \text{lb}\ Cl_2}{1\ \text{lb}\ NH_3}$$

$$\frac{1\ \text{mol}\ Cl_2}{1\ \text{mol}\ NH_3} \times \frac{71\ \text{lb}\ Cl_2}{1\ \text{mol}\ Cl_2} \times \frac{1\ \text{mol}\ NH_3}{1\ \text{mol}\ N} \times \frac{1\ \text{mol}\ N}{14\ \text{lb}\ N} = \frac{71\ \text{lb}\ Cl_2}{14\ \text{lb}\ N}$$

$$= \frac{5.06\ \text{lb}\ Cl_2}{1\ \text{lb}\ N}$$

Impact of $Cl_2:NH_3$ ratio

(in the imaginary world)

- $Cl_2:NH_3 < 4.2:1$
  - NH_2Cl formed
  - Excess NH_3 present after the reaction
- $Cl_2:NH_3 > 4.2:1$
  - Excess Cl_2 was used and (therefore)
  - $NHCl_2$ and NCl_3 are formed
- NH_2Cl is dominant at $4.2:1 \leq Cl_2:NH_3$
- $NHCl_2$ tends to form at $4.2:1 < Cl_2:NH_3 \leq 7.6:1$
- NCl_3 tends to form at $Cl_2:NH_3 > 7.6:1$

Impact of $Cl_2:NH_3$ (as N) ratio

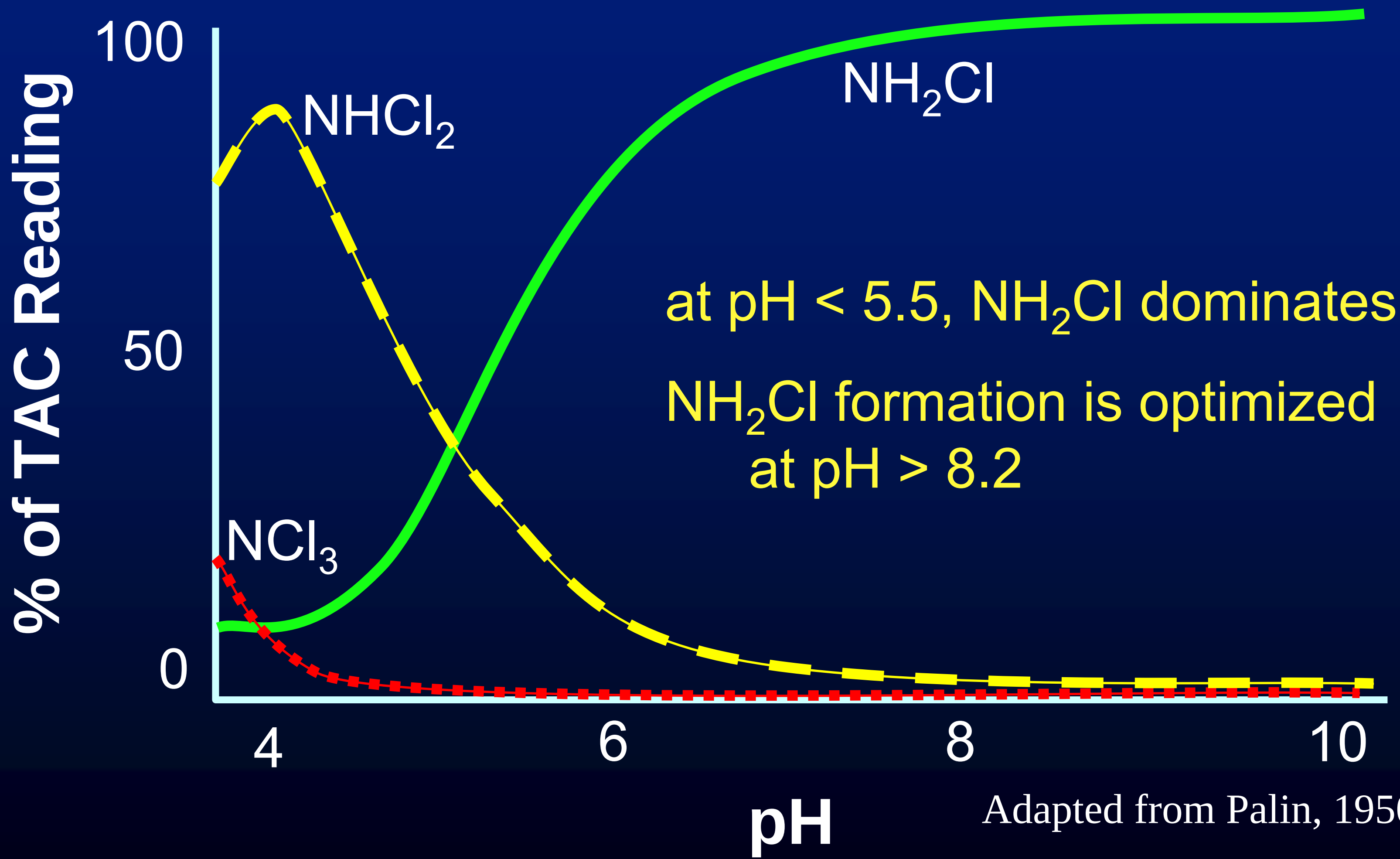
(in the imaginary world)

- $Cl_2:N < 5.1:1$
  - NH_2Cl formed
  - Excess NH_3 present after the reaction
- $Cl_2:N > 5.1:1$
  - Excess Cl_2 was used and (therefore)
  - $NHCl_2$ and NCl_3 are formed
- NH_2Cl is dominant at $5.1:1 \leq Cl_2:N$
- $NHCl_2$ tends to form at $5.1:1 < Cl_2:N \leq 9.3:1$
- NCl_3 tends to form at $Cl_2:N > 9.3:1$

Reality Strikes

- In the real world, other conditions affect the optimum $Cl_2:NH_3$ ratio and the chloramination process
  - pH
  - Temperature
  - Chlorine demand
  - Competing reactions
  - Reaction time
  - Chloramine decay

Real World Impact of pH



at pH < 5.5, NH_2Cl dominates

NH_2Cl formation is optimized at pH > 8.2

Adapted from Palin, 1950

What's the Bottom Line so far?

- There are at least five chemical species that could be present
  - NH_3 (free available ammonia or FAA)
  - HOCl and OCl- (free available chlorine, or FAC)
  - NH_2Cl (monochloramine)
  - $NHCl_2$ (dichloramine)
  - NCl_3 (trichloramine)

combined chlorine

total available chlorine, or TAC

What's the Bottom Line so far?

2) One molecule of FAC reacts with one molecule of FAA to form one molecule of monochloramine
3) FAC and FAA cannot coexist to any significant degree
4) FAC and monochloramine cannot coexist to any significant degree

What’s the Bottom Line so far?

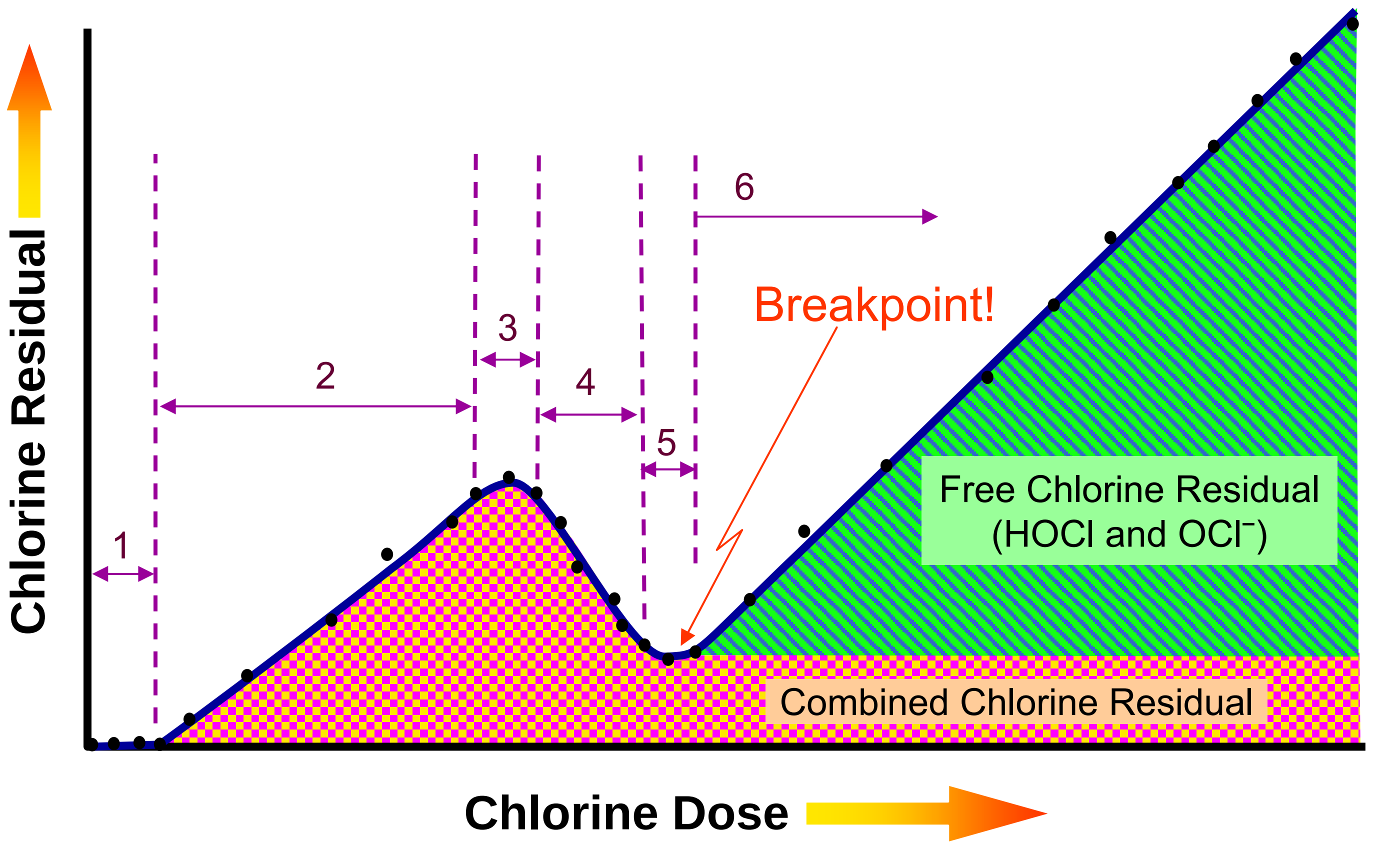
5) If we have the correct ratio, the TAC will neither increase nor decrease
6) An incorrect $Cl_2:NH_3$ ratio will result in excess FAA or the destruction of our target disinfectant (monochloramine)
7) In the real world, we use weight-based units of measurement rather than molecular units

What's the Bottom Line so far?

8) In theory, the correct $Cl_2:NH_3$ ratio is 4.2:1 and the correct $Cl_2:N$ ratio is 5.1:1 (on a weight basis)
9) Real world operating conditions can influence the chloramination process.

The Breakpoint Curve

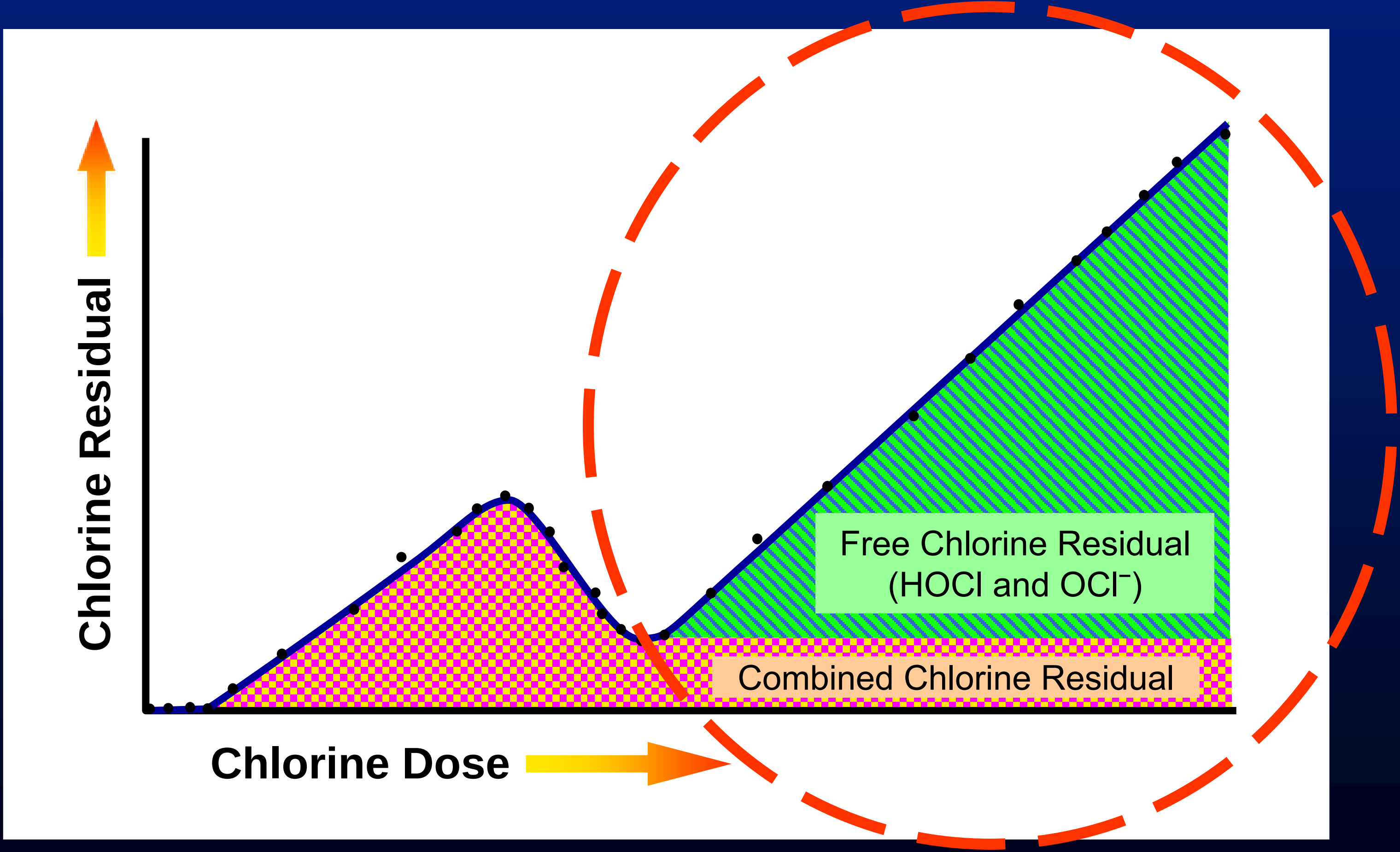
Understanding the Curve



Two Disinfection Scenarios

- Chlorine before Ammonia
  - Primarily for initial disinfection
    - Provides safety factor for chloramine CT
    - Provides preoxidation
- Ammonia before chlorine
  - Primarily for rechlorination
    - Reduces impact of competing reactions

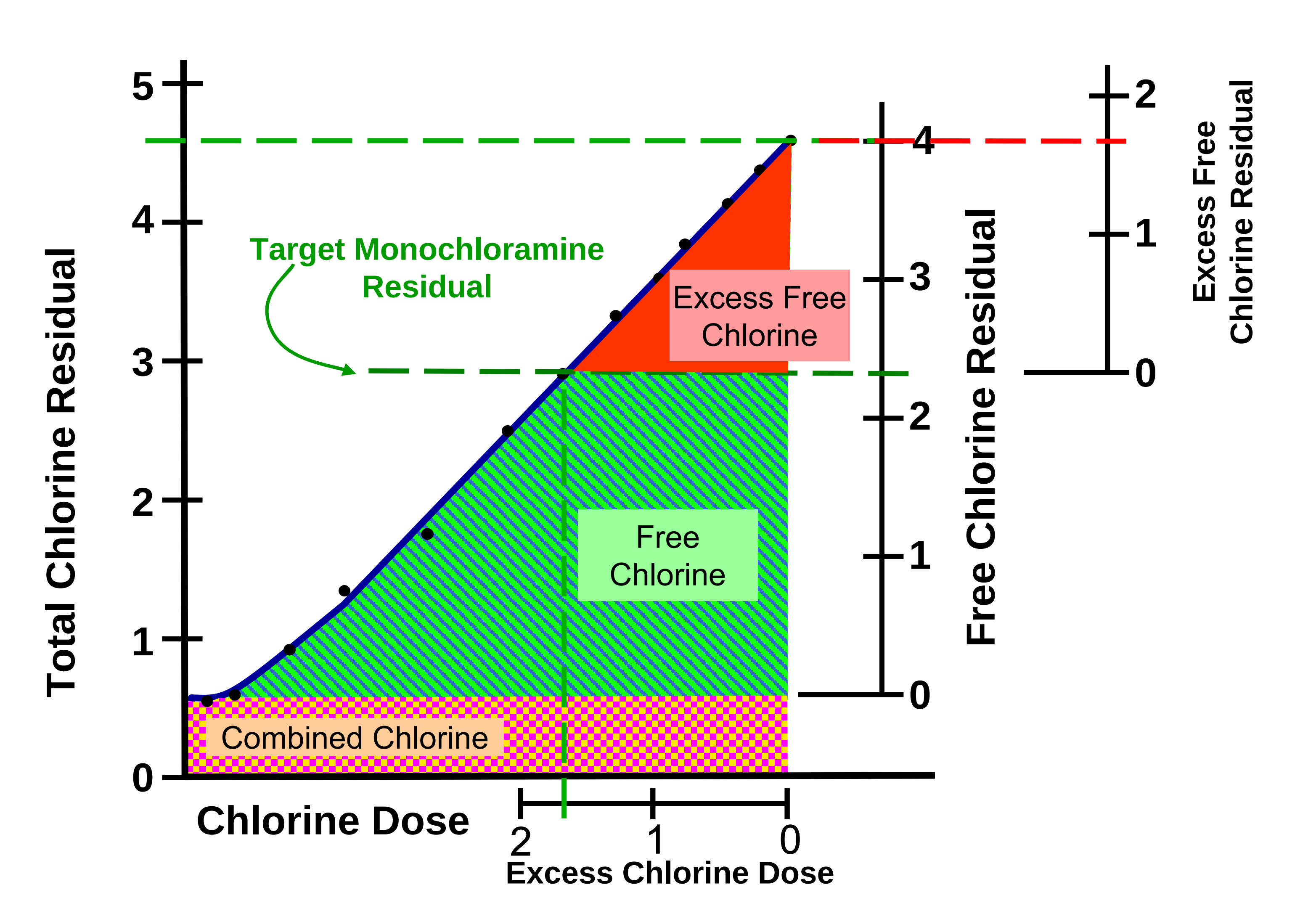
Scenario 1:
Chlorine before Ammonia



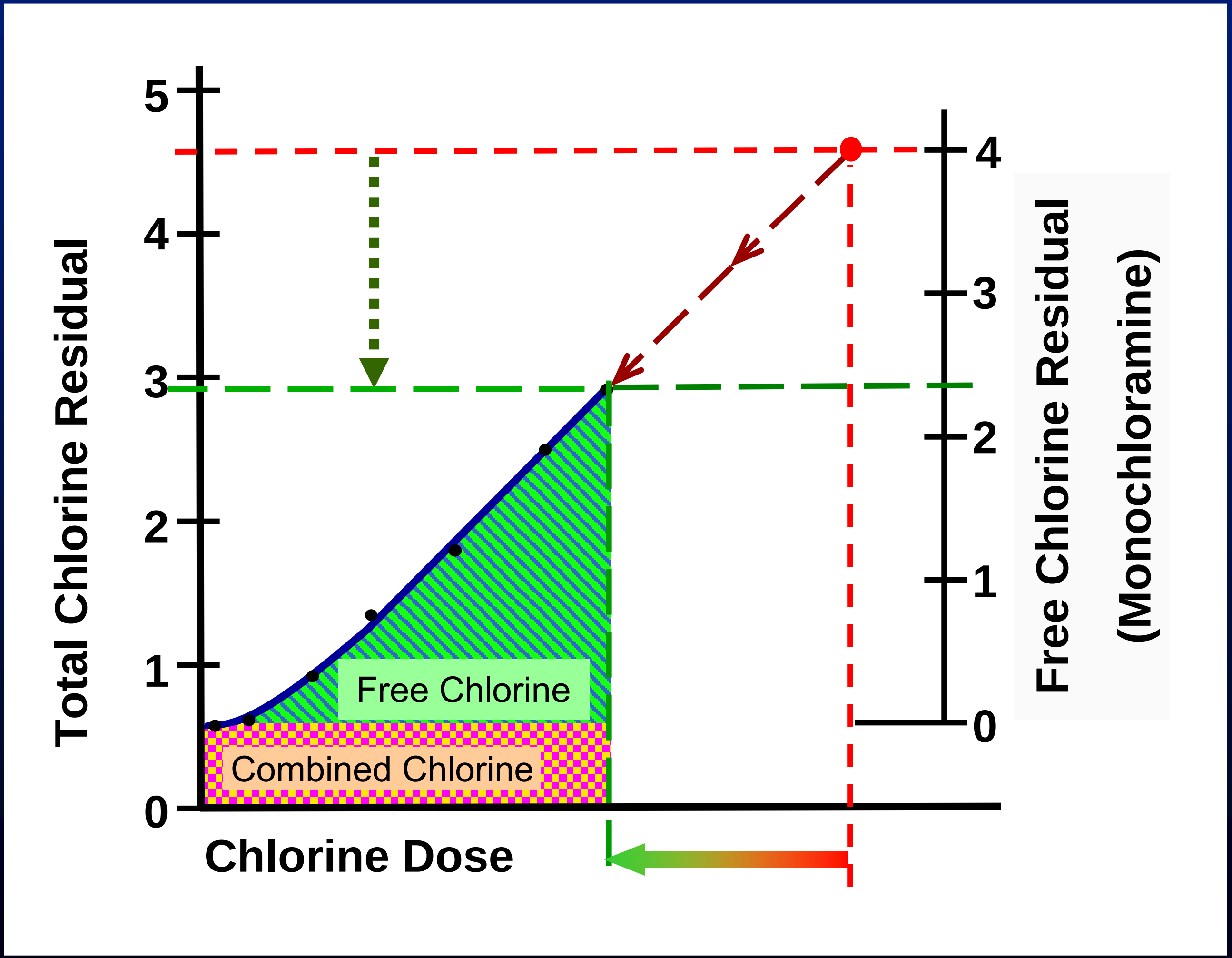
Scenario 1 Data

- Target
  - Mono = 2.3 mg/L
- Currently
  - Mono = trace
  - TAC = 4.6 mg/L
  - FAC = 4.0 mg/L
  - FAA = 0.0 mg/L

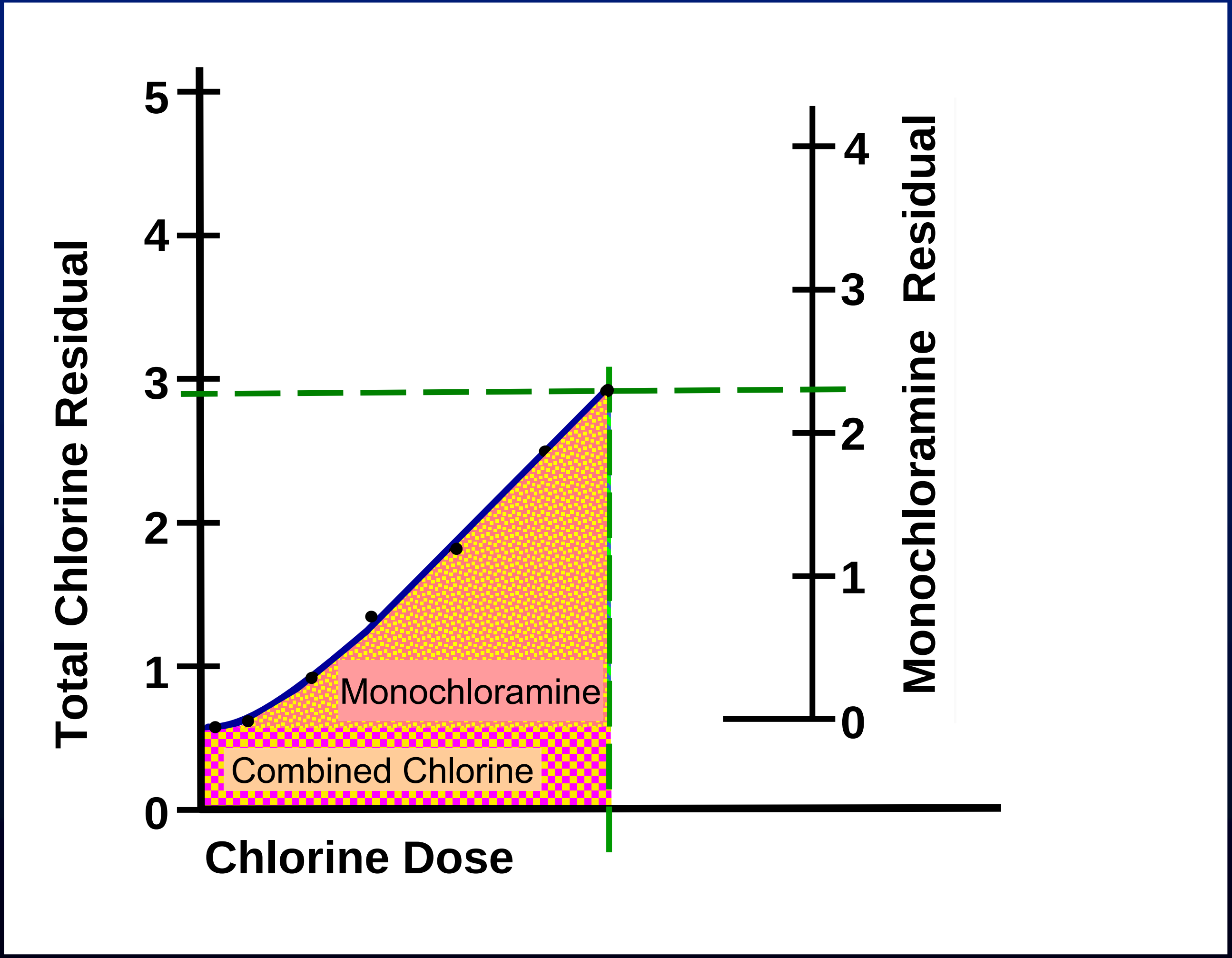
Q1: What does our data tell us?



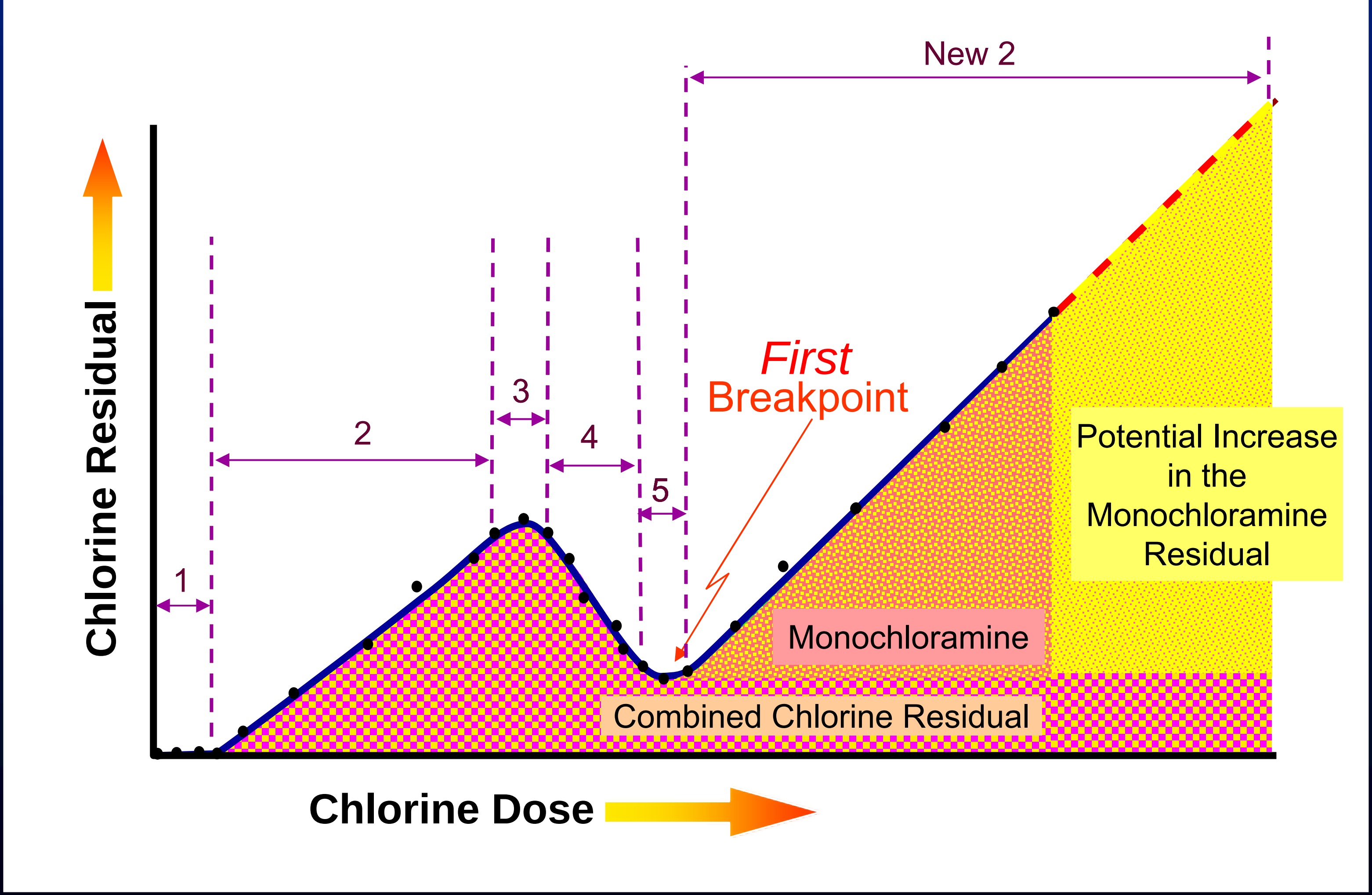
Q2: What happens when we cut chlorine dose by 1.7 mg/L?



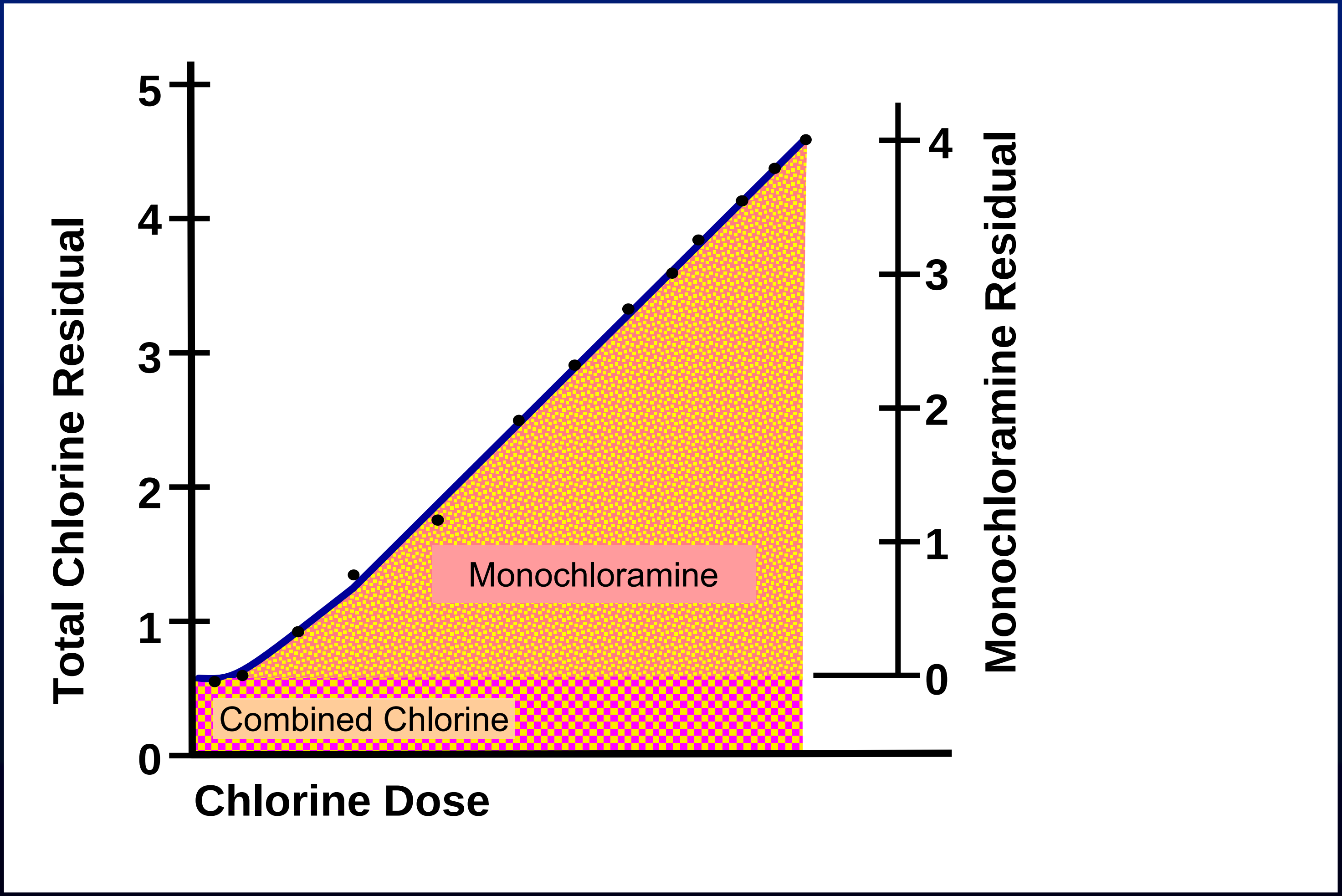
Q3: What happens when we cut Cl_2 by 1.7 and then add NH_3?



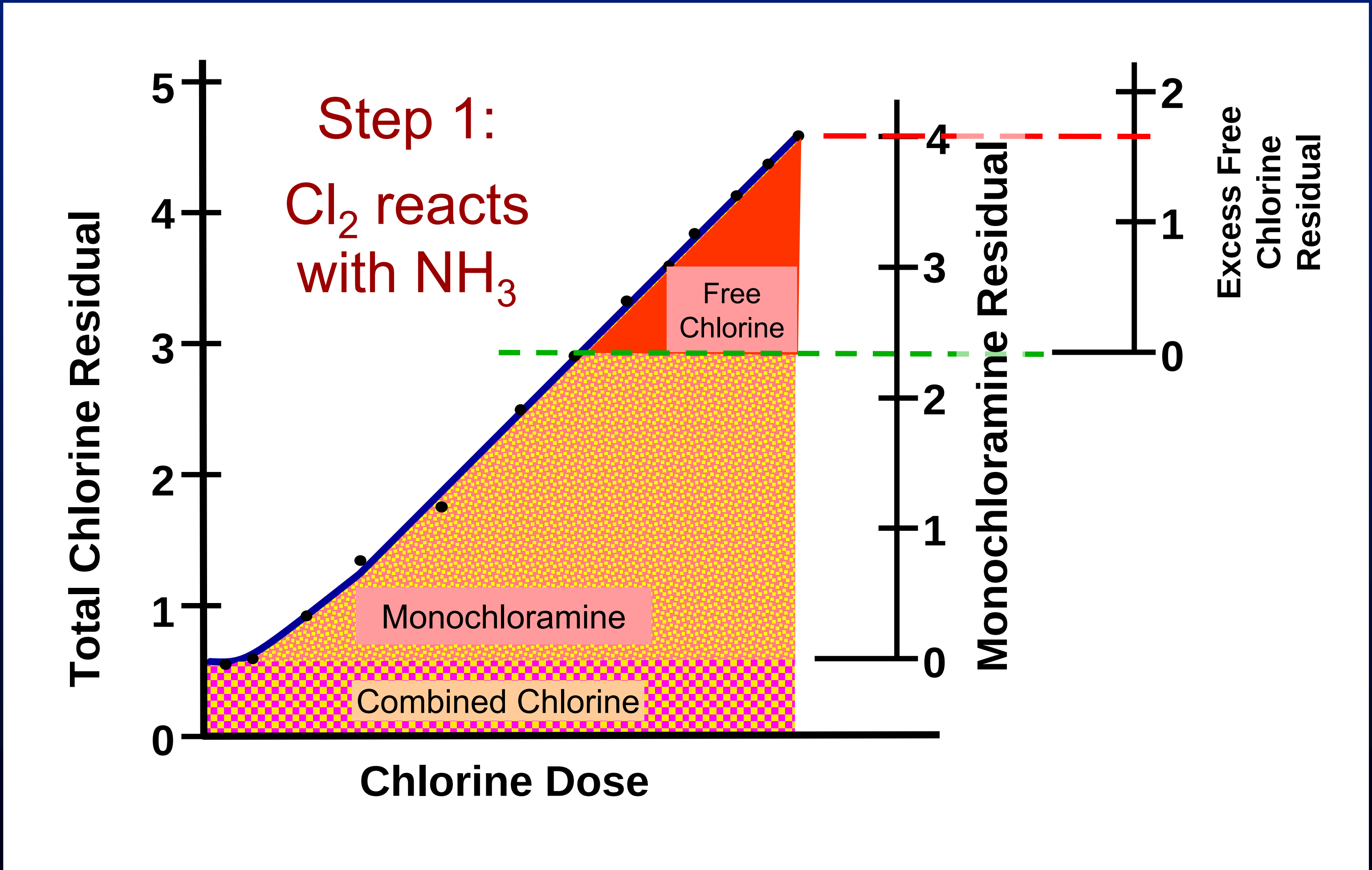
Q4: What happens when we cut Cl_2 and then add excess NH_3?



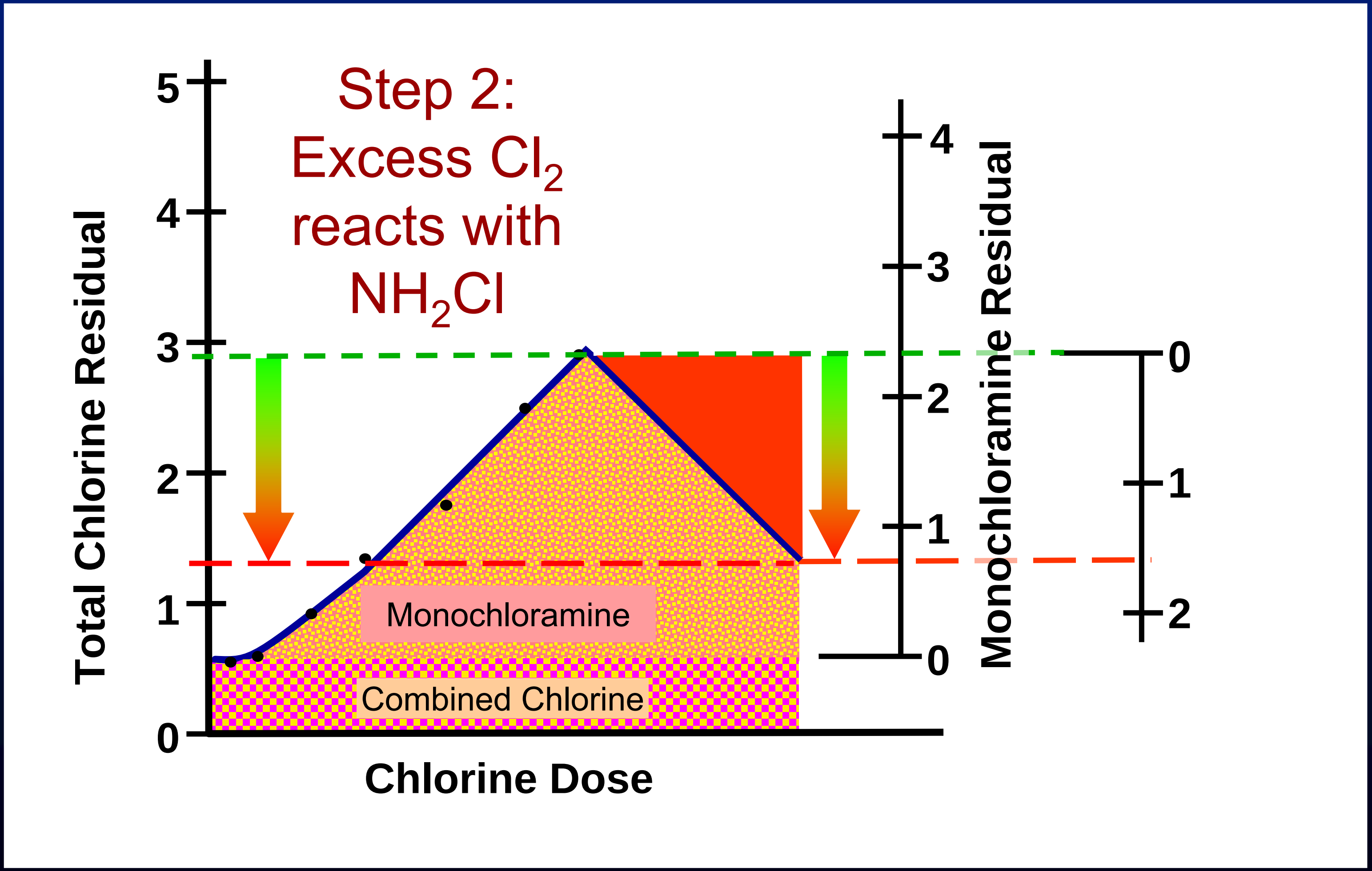
Q5: What happens if we add too much NH_3 without cutting Cl_2?



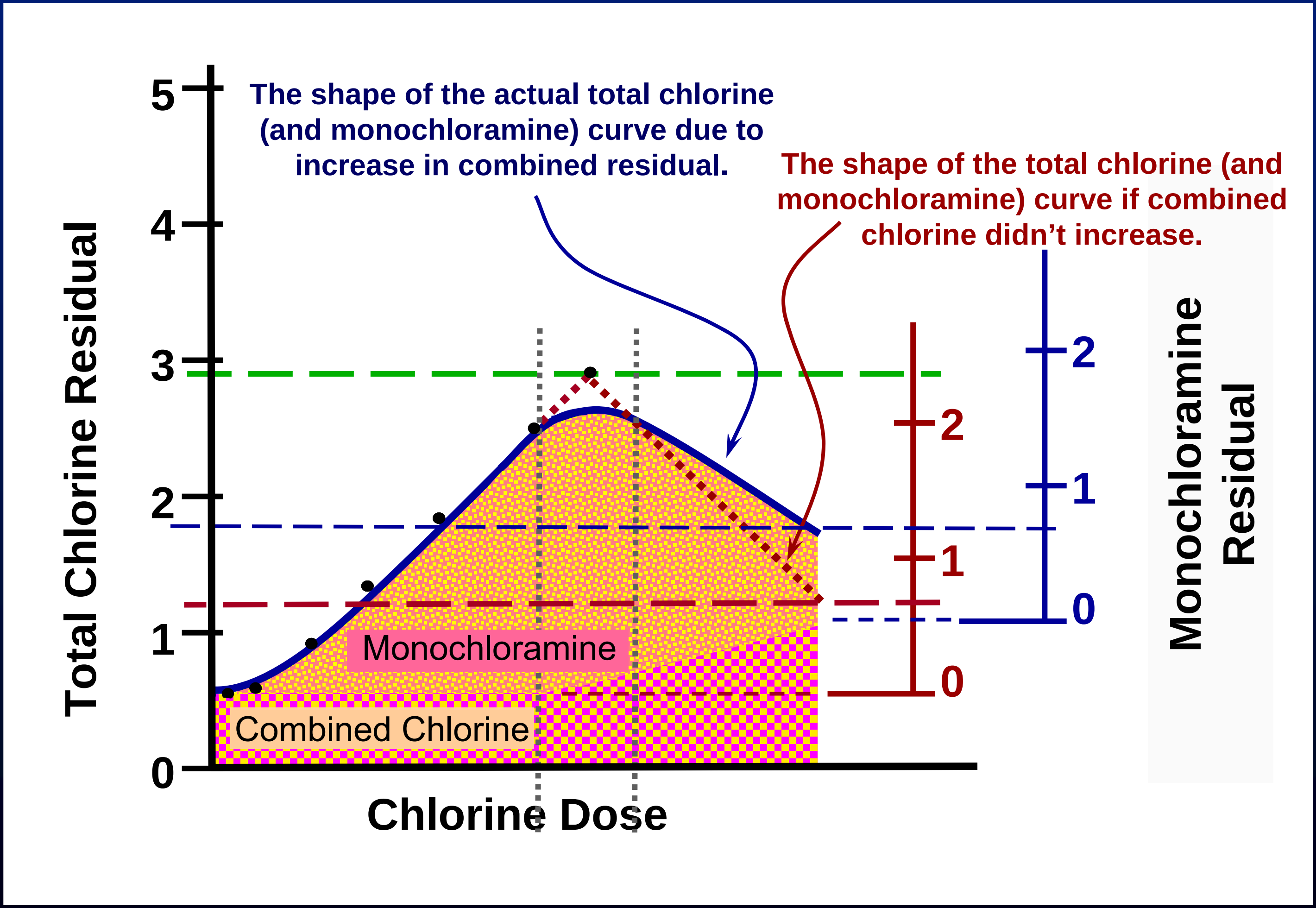
Q6: What happens if we add the right NH_3 without cutting Cl_2?



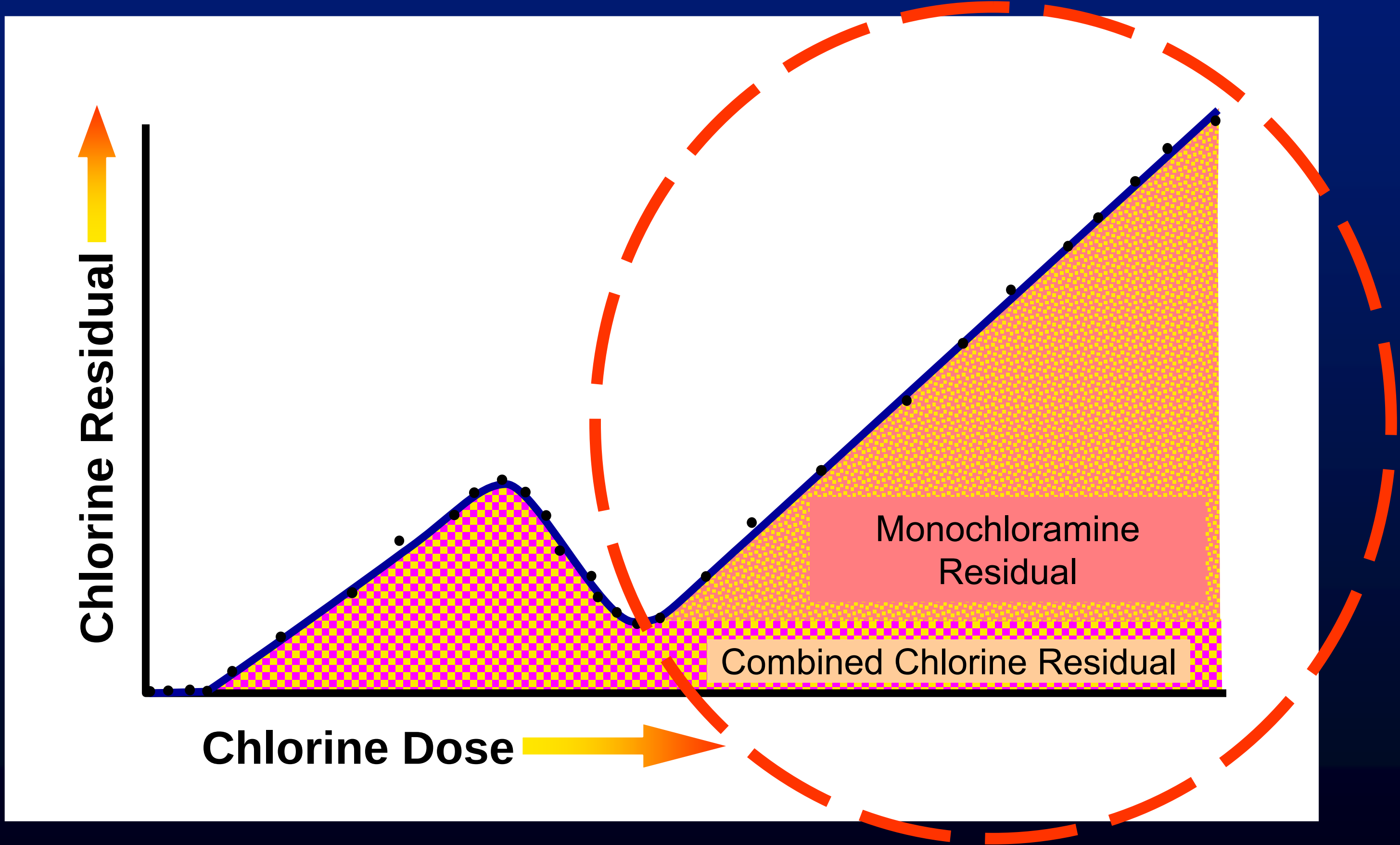
Q6: What happens if we add the right NH_3 without cutting Cl_2?



Q6: What happens if we add the right NH_3 without cutting Cl_2?

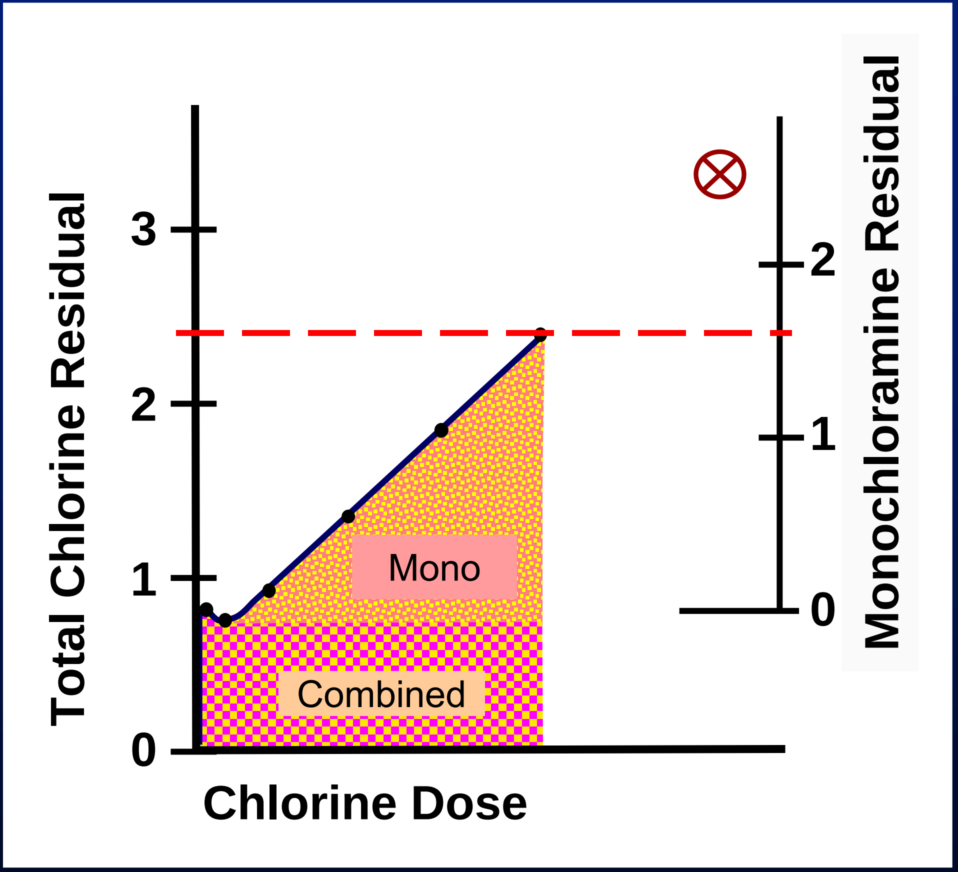


Scenario 2:
Ammonia before Chlorine



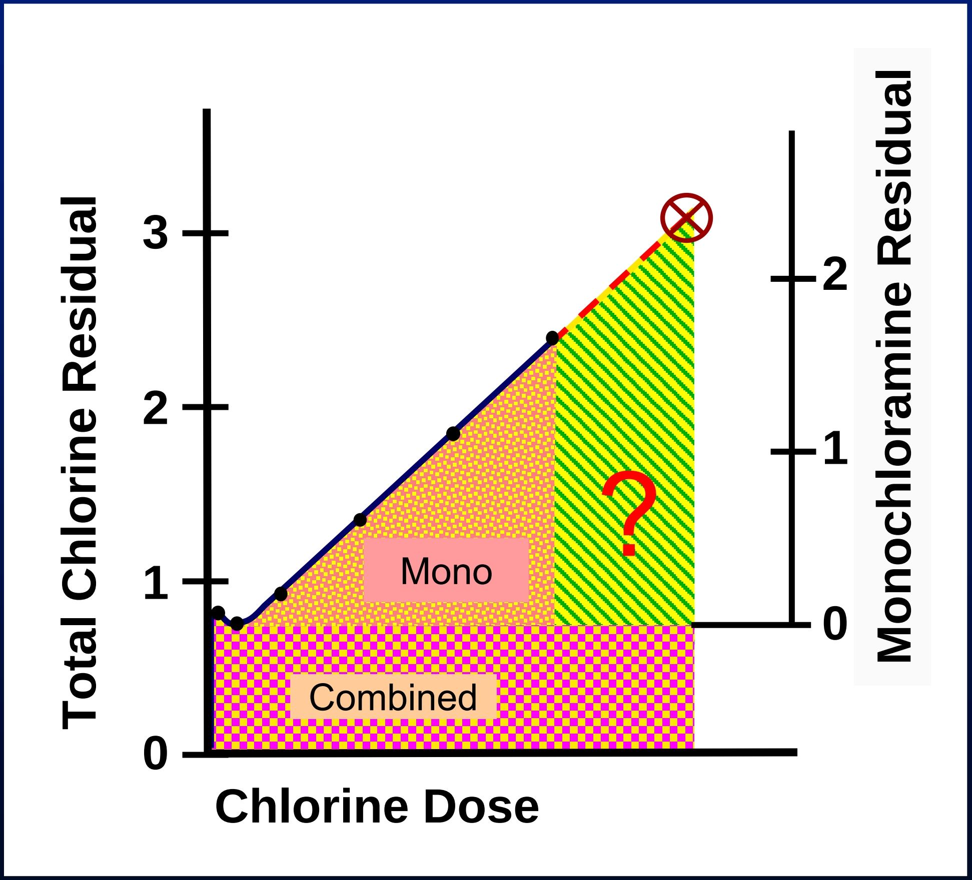
Scenario 2 Data

- Target
  - Mono = 2.3 mg/L
- Currently
  - Mono = 1.6 mg/L
  - TAC = 2.3 mg/L
  - FAC = 0.0 mg/L
  - FAA = 0.2 mg/L



Scenario 2 Questions

- Q1: How much more (if any) NH_3 is needed to reach our target?
- Q2: How much Cl_2 is needed?



What's the Bottom Line?

- The Breakpoint Curve can help operators visualize what is happening during each step of the chloramination process.
- To evaluate the five chemical species that could be present, we need to be able to measure:
  - free available chlorine (FAC),
  - total available chlorine (TAC),
  - monochloramine (mono), and
  - free available ammonia (FAA)

What's the Bottom Line?

3) We can use FAC, TAC, mono, and FAA results to determine where we are on the curve and what general changes need to be made to get where we want to be.

4) If we add enough ammonia, the TAC residual will not change simply because we add ammonia. This is because:
   - One FAC molecule reacts with one FAA molecule to form one mono molecule, and
   - TAC includes FAC, mono, and combined.

What’s the Bottom Line?

5) However, if we have too much FAC present after adding FAA:
   - our mono will be lower than we expected,
   - our combined chlorine level will increase, and
   - our TAC level will drop (but not as much as our mono).

What’s the Bottom Line?

6) Chlorine (or chlorine dioxide or ozone) needs to be added before ammonia when treating undisinfected water.

7) Ammonia should be added before chlorine if we are boosting the residual in water that has already been treated with chlorine, chlorine dioxide, or ozone.

What’s the Bottom Line?

8) Competing reactions can affect the shape of the breakpoint curve. Consequently,
   - It may take slightly more than 1.0 mg/L of chlorine to get 1.0 mg/L of mono, and
   - we may need to have a slight excess of ammonia present.

9) We have to be able to determine how much chlorine and ammonia we need to add to get what we want.

Dosage and Feed Rate Calculations

In Simple Terms

- Chemical dose is the amount of chemical we add divided by the amount of water we put it in.
- Chemical feed rate is the amount of chemical we added divided by the amount of time it took us to add it.

In the Real World

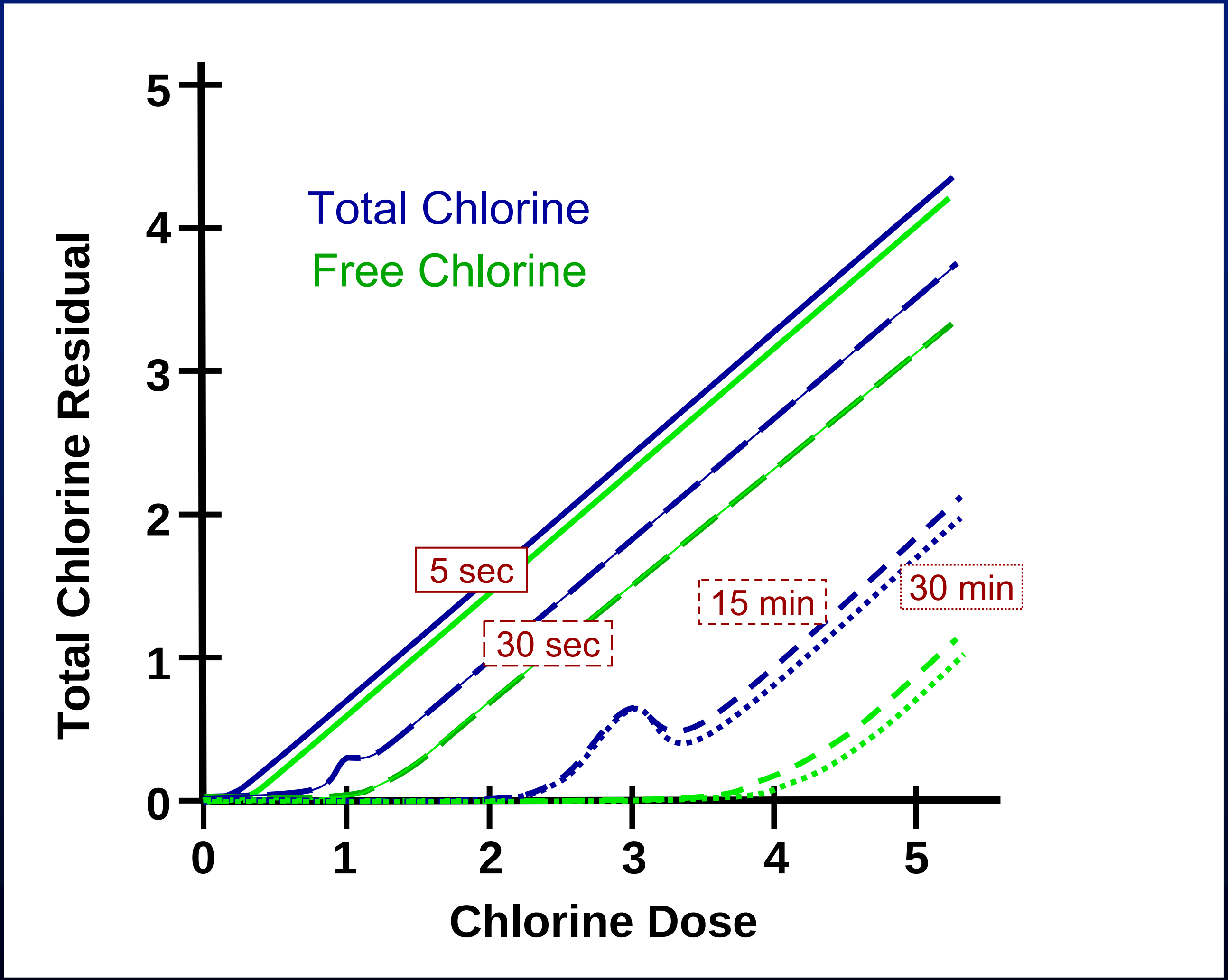
- Dosage and feed rate calculations depend on the molecular formula and concentration of the chemicals used.
- The required dose and feed rates are affected by competing reactions.
- Our ability to control chloramination process is affected by our analytical methods.

Competing Reactions

Reaction Conditions

- Factors that affect reaction rates include:
  - the pH and temperature of the solution
  - the concentration of the reactants and products
- Chemical reactions can occur simultaneously but some are faster than others so time is important

Reaction Time



Analytical Methods

Understand the Method Capabilities & Limitations

- DPD powder pillows
  - Monochloramine interferes with the FAC test

- Amperometric titration (SM 4500Cl–D), DPD-FAS method (SM 4500Cl–F), and DPD colorimetric method (SM 4500Cl–G),
  - Can distinguish between FAC, Mono, and Combined (Di and Tri)

Understand the Method Capabilities & Limitations

- Hach Indophenol
  - Monochloramine
  - FAA
- Ion Specific Electrode
  - FAA
- Hach Salicylate
  - Low-level Monochloramine and FAA

TCEQ Suggestions
(for Field Investigators & Small Plants)

- TAC and FAC
  - DPD powder pillows and colorimeter
- Mono and FAA
  - Hach Indophenol (Monochlor F)

Understanding the Results

Compound & Concentration	Molecular Formula	Molecular Weight	Reported Result
0.1 millimoles of monochloramine (NH_2Cl)	Cl_2	71	7.1 mg/L as Cl_2
	NH_2Cl	51.5	5.15 mg/L as NH_2Cl
	N	14	1.4 mg/L as N
0.01 millimoles of free available ammonia (NH_3)	NH_3	17	0.17 mg/L as NH_3
	N	14	0.14 mg/L as NH_3–N

TCEQ Suggestions

- Have the instrument report TAC, FAC, and Mono in units of mg/L as Cl_2
- Have the instrument report FAA in units of mg/L as NH_3
- If the instrument does not have the option, use conversion factors, e.g.
  - mg/L NH_3 = 1.21 times mg/L NH_3–N
  - mg/L Cl_2 = 1.29 times mg/L NH_2Cl

Applied Chemical Dose,
Applied Reactant Dose,
and
Effective Reactant Dose

Parts per Million

- Chemical dose should be described on a weight-to-weight (w/w) basis whenever possible.
- Using a w/w basis compensates for molecular formula and chemical concentration
- On a weight-basis,
  1 ppm = 1 lb per 10^6 lbs = 1 mg/L

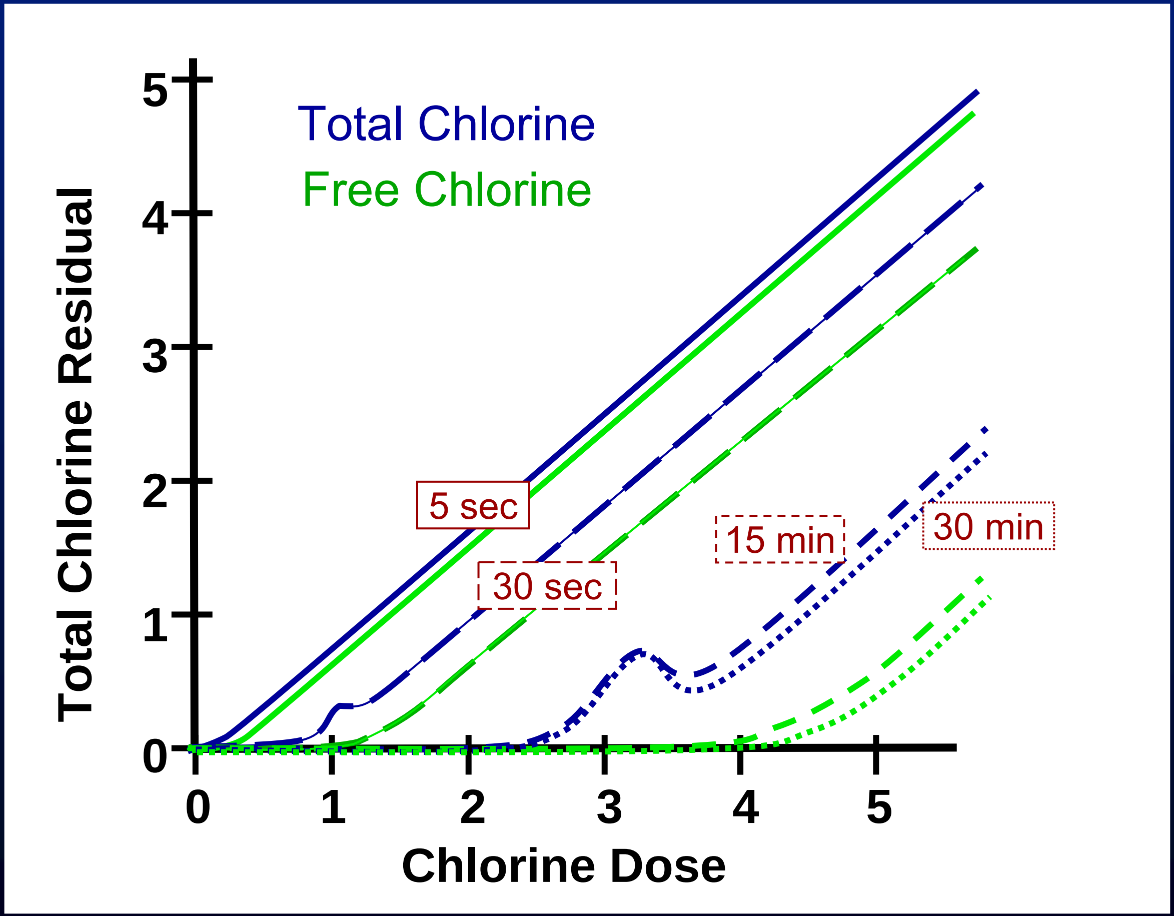
Molecular Formula and Chemical Concentration

- Many of the chemicals that plants use are molecular compounds or solutions that contain materials other than the molecular group that participates in the chemical reaction.
- Dosage and feed rate calculations must compensate for the “purity” of the chemicals used.

Applied Chemical Dose vs. Applied Reactant Dose

- Applied chemical dose is the amount of chemical that we add divided by the amount of water we add it to.
- Applied reactant dose is the amount of actual reactant (after we correct for "purity") that we add divided by the amount of water we add it to.

Remember competing reactions can consume some of our reactants



Applied Reactant Dose vs. Effective Reactant Dose

- Applied reactant dose is the amount of “pure” reactant we added divided by the amount of water we added it to.
- Effective reactant dose is the amount of reactant that remained (after competing reactions) divided by the amount of water we added it to.

Chlorine Dose and Feed Rate

- Chlorine is available in a variety of forms and concentrations
  - chlorine gas is 100% available chlorine
  - calcium hypochlorite is a solid that generally contains 60 – 75% available chlorine
  - sodium chlorite is a liquid that contains 5 – 12% available chlorine

To feed 10 lbs per day of Cl2 using gas chlorine:

- Data:
  - Chlorine gas is 100% available chlorine
- Calculations:
  - Rotameter setting is 10 ppd . . . maybe

Gases are Compressible Fluids

- Each gas has a unique specific gravity (density) that changes with temperature and pressure.
- Rotameters are calibrated with a specific gas under specific pressure at a specific temperature using a specific float design and material.

Typical Rotameter Design Data

Float Material	Specific Gravity	Gas	Specific Gravity[1]
Teflon	2.2	Air	1.0
Glass	2.53	Ammonia	0.593
Sapphire	3.99	Chlorine	2.45
Titanium	4.50	Nitrogen	0.967
316 SS	8.02	(1) At STP which is: T = 70°F P = 1 atm (14.7 psi)	
Carboloy	15.00		

To feed 10 lbs per day of Cl_2 using calcium hypochlorite:

- Data:
  - The $Ca(OCl)_2$ contains 65% available Cl_2
  - The feed solution contains 10 lbs of $Ca(OCl)_2$ in 10 gallons of water
- Calculations:

$$\frac{10\ \text{lbs Cl}_2}{\text{day}} \times \frac{\text{lb Ca(OCl)}_2}{0.65\ \text{lbs Cl}_2} = \frac{15.4\ \text{lbs Ca(OCl)}_2}{\text{day}}$$

$$\frac{15.4\ \text{lb Ca(OCl)}_2}{\text{day}} \times \frac{10\ \text{gal of solution}}{10\ \text{lb Ca(OCl)}_2} = \frac{15.4\ \text{gal of solution}}{\text{day}}$$

To feed 10 lbs per day of Cl_2 using sodium hypochlorite:

- Data:
  - The NaOCl bleach contains 10% available Cl_2
  - The bleach has a specific gravity of 1.28
- Calculations:

$$\frac{10 \text{ lbs } Cl_2}{\text{day}} \times \frac{\text{lb bleach}}{0.10 \text{ lbs } Cl_2} = \frac{100 \text{ lbs bleach}}{\text{day}}$$

$$1 \text{ gallon of bleach} = 1.28 \times 8.34 = \frac{10.68 \text{ lbs of bleach}}{\text{gallon of bleach}}$$

$$\frac{100 \text{ lb bleach}}{\text{day}} \times \frac{\text{gal bleach}}{10.68 \text{ lb bleach}} = \frac{9.4 \text{ gal of bleach}}{\text{day}}$$

Summary Example

- Data:
  - Water flow rate at the point of application is 167 gpm = 0.24 MGD = 2.0 million ppd
  - Chemicals are applied at the rate calculated in each of the individual examples
  - Chlorine demand at this application point = 2.0 mg/L

Summary Example

	Chlorine Gas	Calcium Hypochlorite	Sodium Hypochlorite Bleach
Chemical Feed Rate (ppd) (from the example)	10	15.4	100
Water Flow Rate (million ppd)	2.00	2.00	2.00
Applied Chemical Dose (ppm)	5	7.7	50
Reactant feed rate (ppd of Cl_2)	10	10	10
Applied Reactant Dose (ppm of Cl_2)	5.0	5.0	5.0
Chlorine Demand (mg/L of Cl_2)	2.0	2.0	2.0
Effective Reactant Dose (ppm of Cl_2)	3.0	3.0	3.0

Ammonia Dose and Feed Rate

- Ammonia, like chlorine, is available in a variety of forms and concentrations
  - ammonia gas is 100% FAA
  - ammonium hydroxide and ammonium sulfate are available in both solid and liquid forms
- Unlike in the case of chlorine, the concentration of ammonia compounds can be described in a variety of ways

Ammonia Compound Composition

Compound	Molecular Formula	Molecular Weight	Available Ammonia	
			As NH_3	As N
anhydrous ammonia (gas)	NH_3	17	100%	82.4%
ammonium hydroxide (dry)	NH_4OH	35	48.6%	40.0%
ammonium sulfate (dry)	$(NH_4)_2SO_4$	132	25.8%	21.2%

Ammonia Solution Concentration

It is extremely important to know exactly how the vendor specs his product.

- Chlorine concentration is almost always described in terms of "% available chlorine on a $^{w}/_{w}$ basis"
- No such standard exists for ammonia solutions. Depending on the vendor, one pound of a 25% LAS product could contain:
  - 0.25 lb of dry ammonium sulfate, or
  - 0.25 lb of ammonia, or
  - 0.25 lb of nitrogen

To feed 2 lbs per day of NH_3 using anhydrous ammonia:

- Data:
  - Anhydrous ammonia is 100% available NH_3
- Calculations:
  - Rotameter setting is 2 ppd . . . maybe

To feed 2 lbs per day of NH_3 using liquid ammonium sulfate:

- Data:
  - Ammonium sulfate $(NH_4)_2SO_4$ contains two ammonium (NH_4) groups and therefore two ammonia (NH_3) molecules
  - 132 lbs of $(NH_4)_2SO_4$ contains 34 lbs of NH_3
  - The LAS contains 38% ammonium sulfate ($^w/_w$)
  - The LAS has a specific gravity of 1.23

To feed 2 lbs per day of NH_3 using liquid ammonium sulfate:

- Calculations:

$$\frac{2\ \text{lbs}\ NH_3}{\text{day}} \times \frac{132\ \text{lb}\ (NH_4)_2SO_4}{34\ \text{lbs}\ NH_3} \times \frac{\text{lb LAS}}{0.38\ \text{lbs}\ (NH_4)_2SO_4} = \frac{20.4\ \text{lbs LAS}}{\text{day}}$$

$$1\ \text{gallon of LAS} = 1.23 \times 8.34 = \frac{10.26\ \text{lbs of LAS}}{\text{gallon of LAS}}$$

$$\frac{100\ \text{lb LAS}}{\text{day}} \times \frac{\text{gal LAS}}{10.68\ \text{lb LAS}} = \frac{2.0\ \text{gal of LAS}}{\text{day}}$$

Notice: gpd of LAS = ppd of ammonia (as NH_3) when the plant feeds this specific product

What’s the Bottom Line?

- We always need to be aware of the potential impact of competing reactions and the time that is available for them to occur.
- We must be aware of and understand how our instruments are reporting our results before we can interpret the data

What’s the Bottom Line?

3) If possible, analytical instruments should be set to:
   a) report FAC, TAC, and mono levels as “mg/L as Cl_2”
   b) report FAA levels as “mg/L as NH_3”

4) It is extremely important to understand the product specifications

What's the Bottom Line?

5) Chemical dosage should be calculated on a weight-to-weight ($^{w}/_{w}$) basis whenever possible

6) 1 ppm ($^{w}/_{w}$) = 1 lb/10^6 lbs = 1 mg/L

7) There is an important difference between:
   a) Applied Chemical Dose
   b) Applied Reactant Dose
   c) Effective Reactant Dose

What's the Bottom Line?

7a) Applied Chemical Dose:

The amount of chemical we add divided by the amount of water we put it in

7b) Applied Reactant Dose:

The amount of reactant (contained in the chemical we added) divided by the amount of water we put it in

What's the Bottom Line?

7c) Effective Chemical Dose:

The amount of reactant (contained in the chemical we added) that is actually available (after any competing reactions) to form our desired product divided by the amount of water we put it in

What's the Bottom Line?

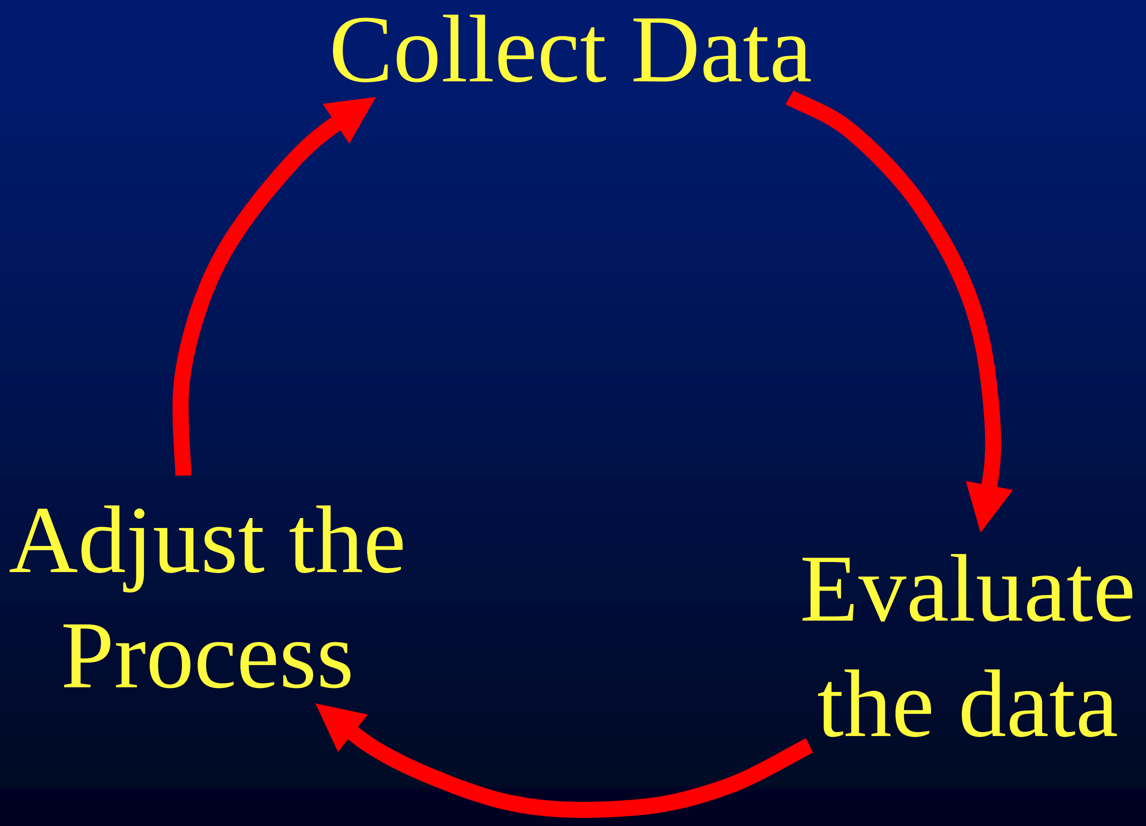
8) It is important to understand how to set the chemical feed equipment

9) Plants that feed liquid chemicals need to have a hydrometer (or some other means) to check specific gravity

10) It is important to know the water flow rate at each point of chemical application

Applying the Concepts

Chuck Schwarz's Simplified Process Control Loop



Applying the Concepts . . . in a practical way

- What do we need to measure to control the process?
- Where is the best spot to test for it?
- What results are we looking for?
- What do we do if we don’t get them?

Collecting the Data

For each chemical application point, we need to know:

1) our current FAC, TAC, mono, and FAA levels
2) our target FAC, TAC, and mono residuals and our target FAA level
3) our current chemical feed rate and water flow rate
4) the molecular weight and formula for each chemical we are using
5) the concentration (on a $^{w}/_{w}$ basis) and specific gravity of each liquid chemical

What do we need to measure and why?

1) FAC . . . to find out
   a) if we added the right amount of Cl_2
   b) exactly how much NH_3 is needed to form mono

2) FAA . . . to find out
   a) if we applied to much NH_3
   b) exactly how much Cl_2 is needed to reduce NH_3 levels

What do we need to measure and why?

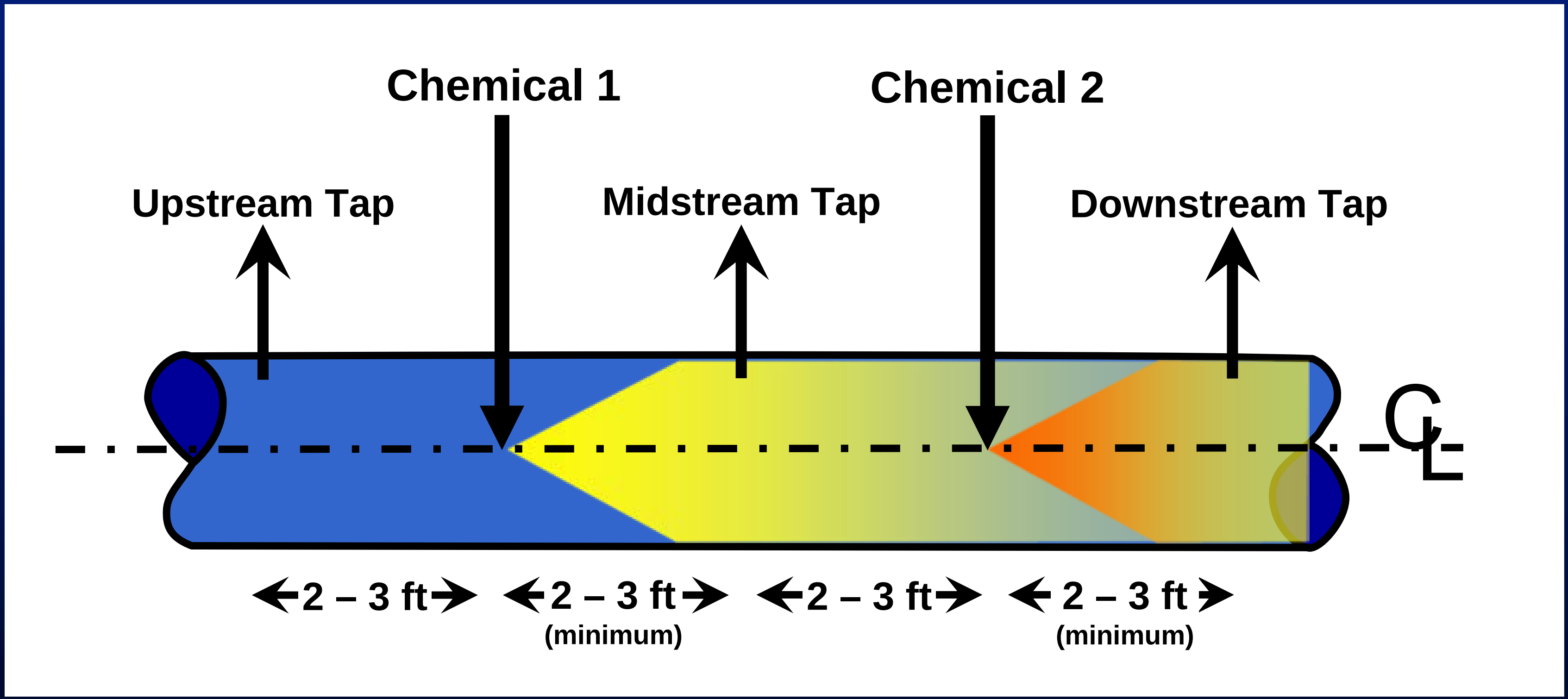
3) Monochloramine . . . to find out
   - if we added the right amount of Cl_2 and NH_3

4) TAC . . . to find out
   - if we made any di- or trichloramine
   - how much difference we should expect between TAC and monochloramine levels after we add NH_3

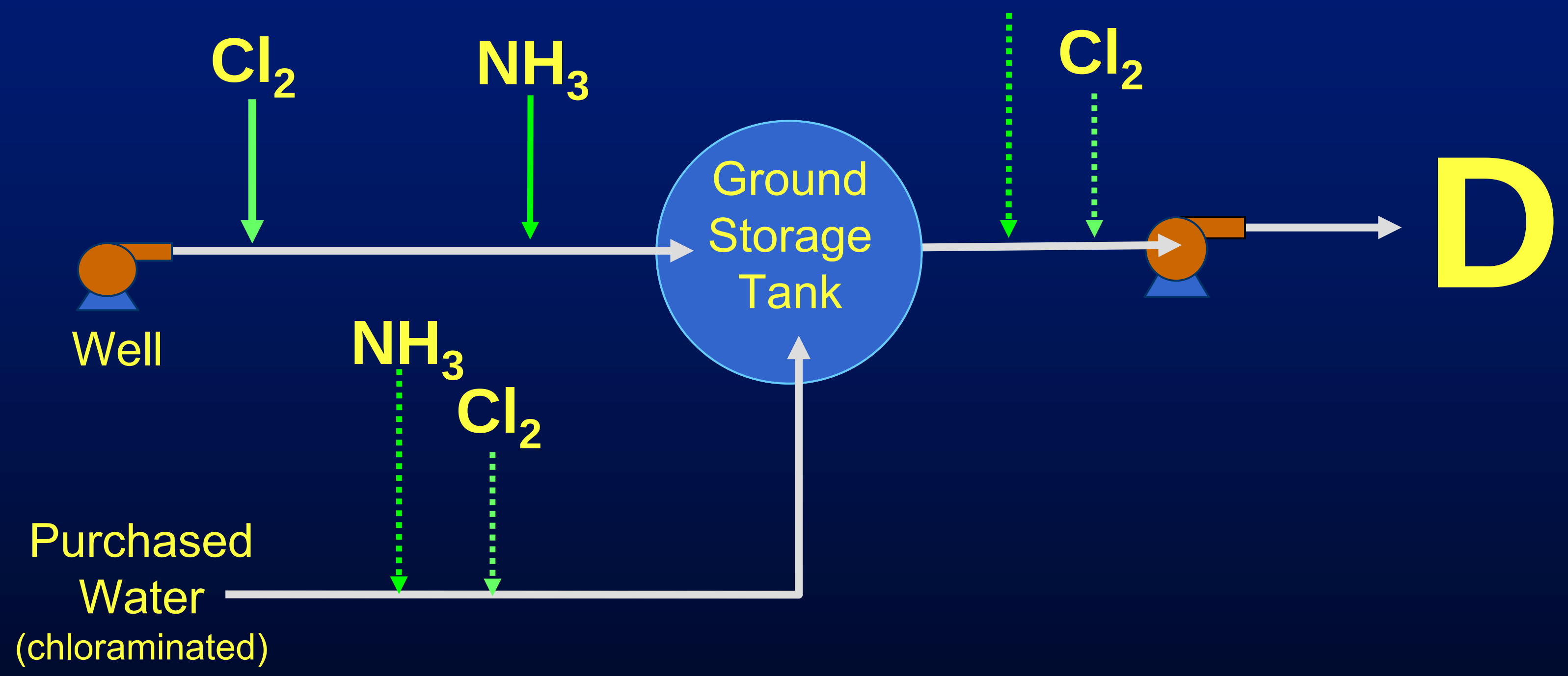
Where should we test?

- For regulated parameters . . .
  At every location required by regulations
  - At the end of the disinfection zone
  - At the point of entry to distribution
- For process control parameters . . .
  At every critical control point
  - Upstream of the chemical injection point
  - Downstream of the chemical injection point

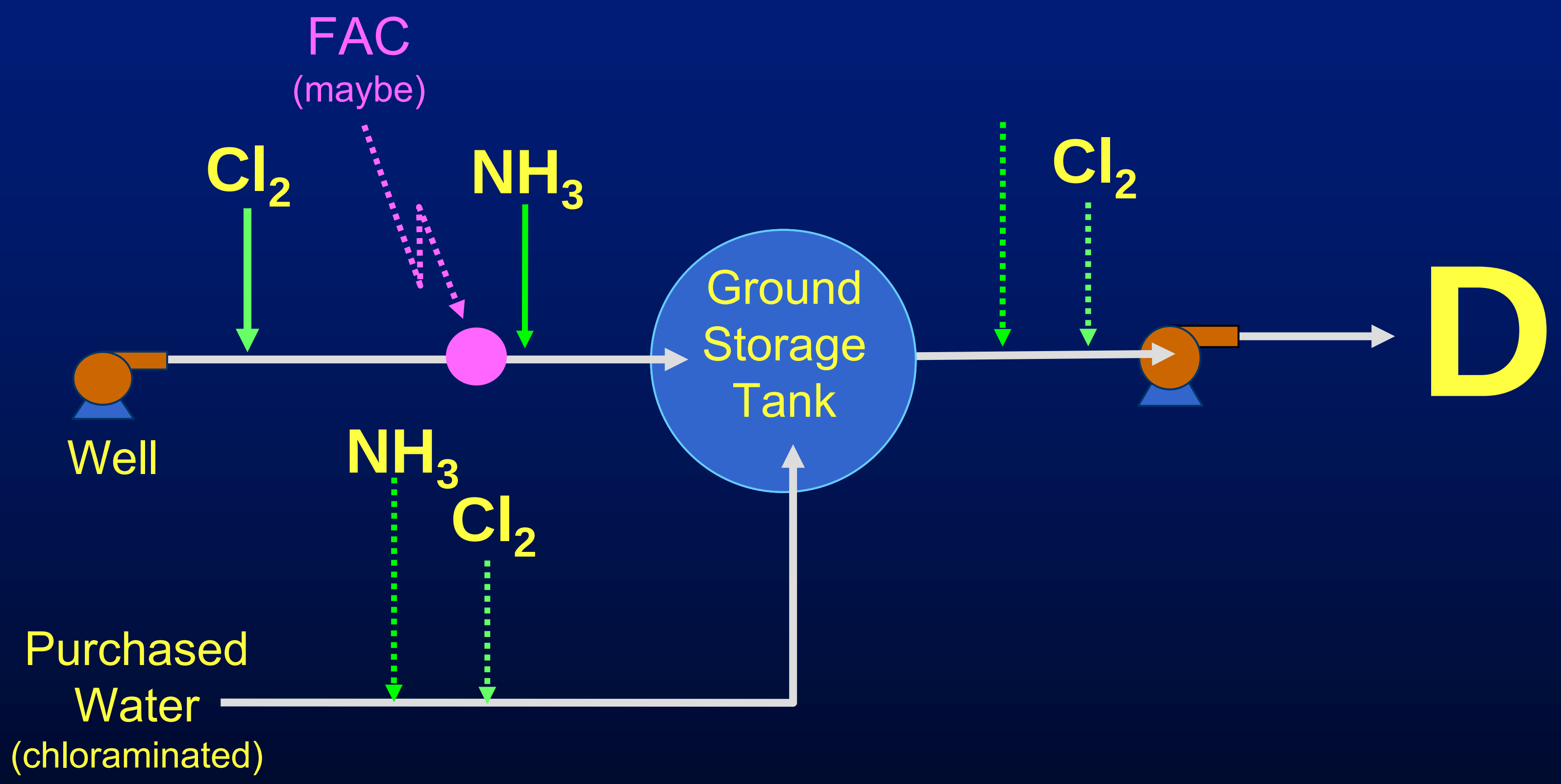
Where should we test?



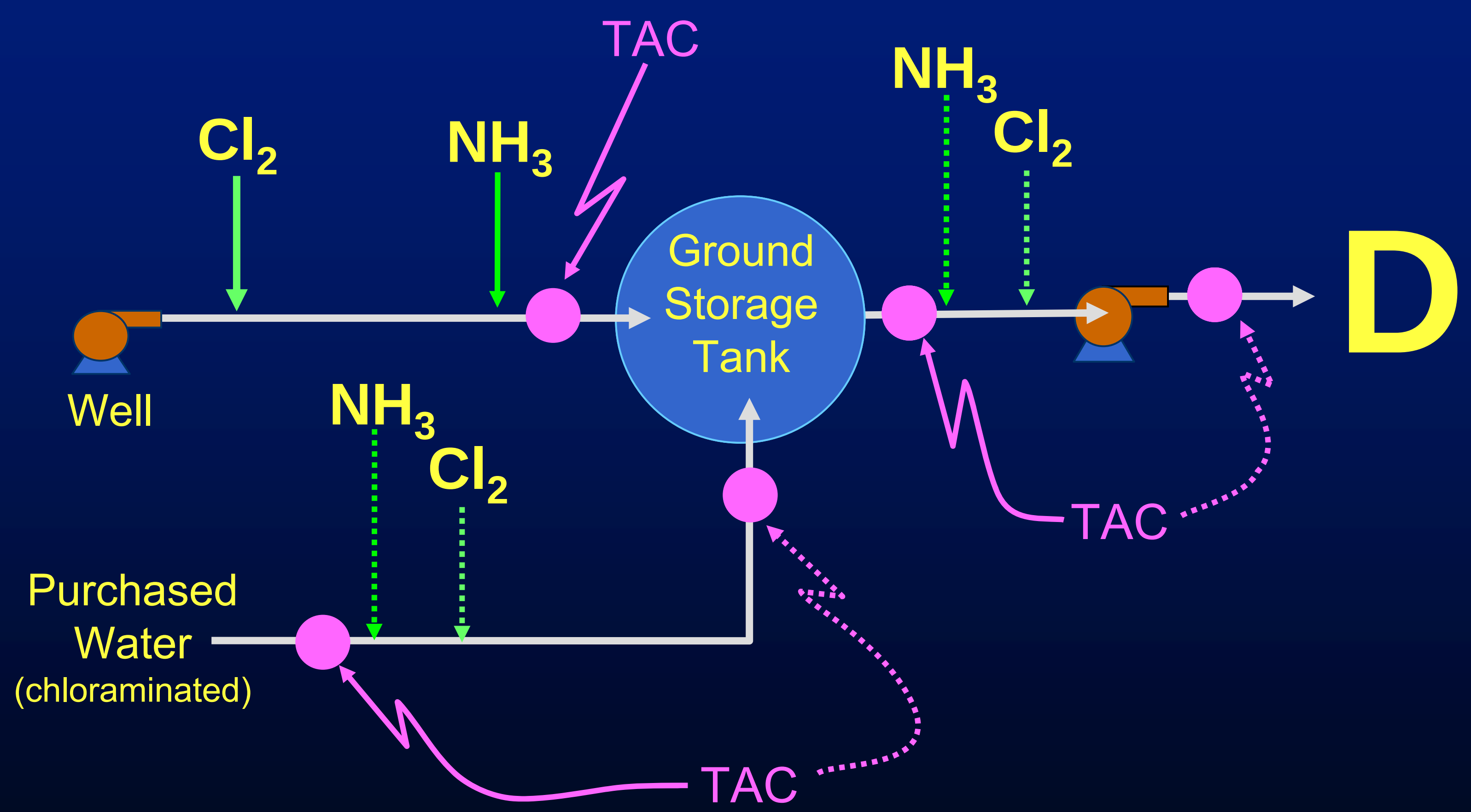
Plant Schematic and Feed Points



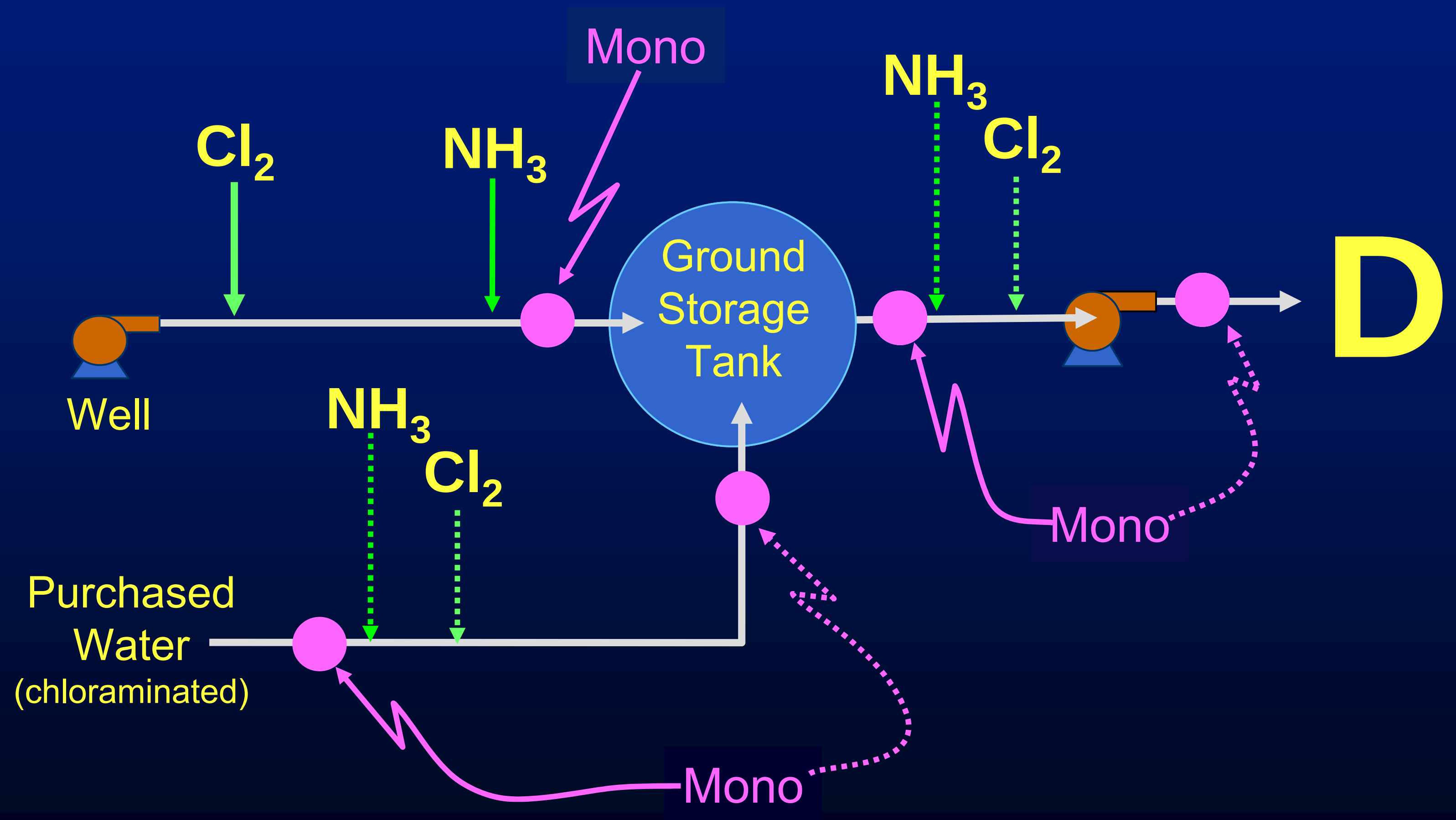
Where to Measure FAC



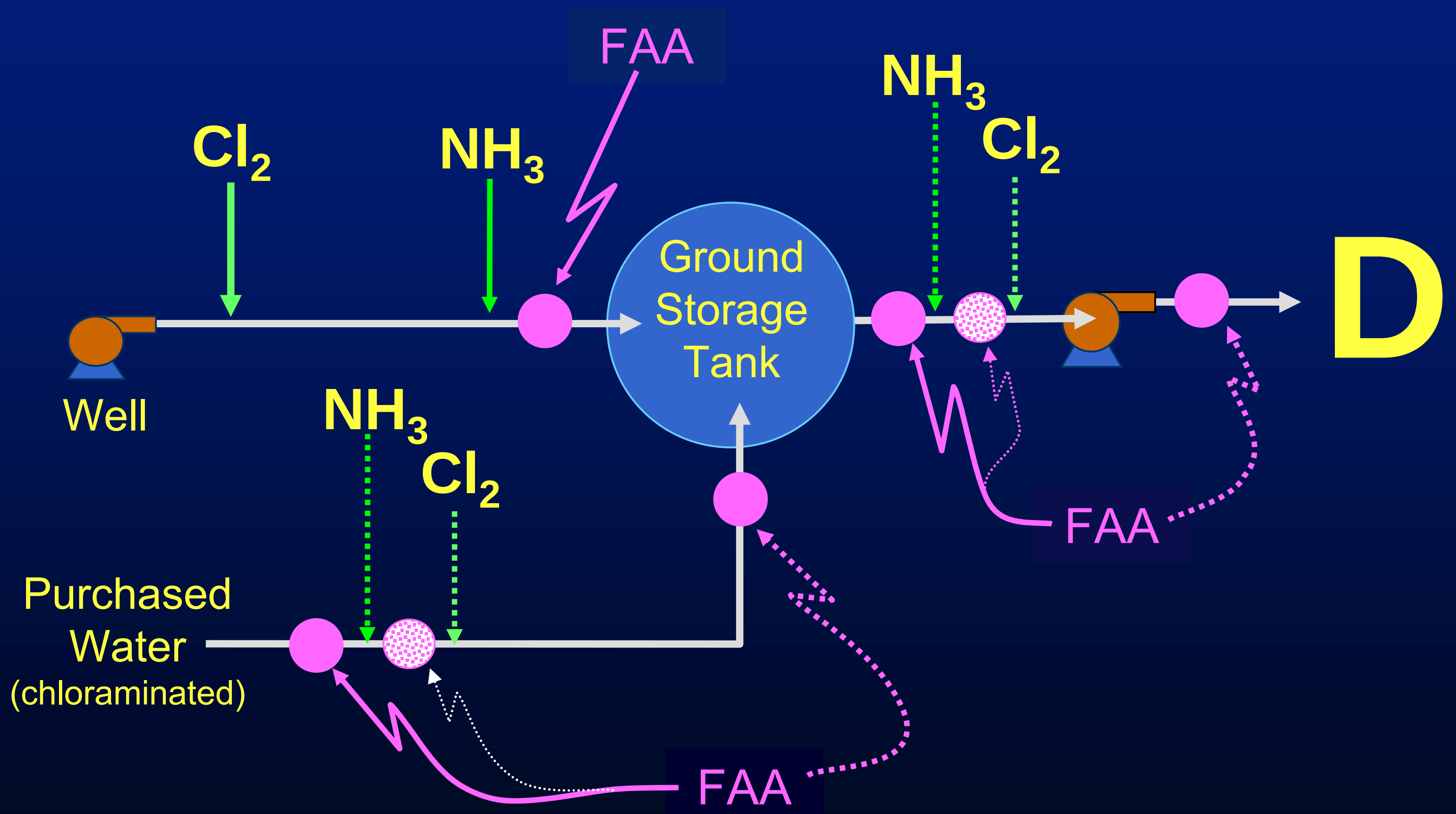
Where to Measure TAC



Where to Measure NH_2Cl



Where to Measure FAA



Evaluating the Data

For each chemical application point, we need to determine:

1) our performance target(s) and
2) our acceptable range(s).

What are our general objectives?

- If Cl_2 is added before NH_3
  - FAC = Target NH_2Cl
- If NH_3 is added before Cl_2
  - FAA = Target NH_2Cl ÷ target Cl_2:NH_3 ratio

What are our general objectives? (cont)

- After adding the Cl_2 and NH_3
  - NH_2Cl = Target NH_2Cl
  - Minimal change in the combine chlorine i.e., TAC – FAC = TAC – NH_2Cl
  - FAA as NH_3 is within acceptable range

What should the targets be?

- FAC, TAC, and mono
  - Within the plant, targets will probably be based on CT requirements
  - At the HSPS, targets will probably be based on distribution system needs
- FAA
  - Within the plant, targets will probably be based on monochloramine targets
  - At the HSPS, FAA as NH_3 = 0.05 – 0.10 mg/L

What's an acceptable upper limit?

- For FAC, TAC, and Mono
  - probably no more than 1.0 – 1.5 mg/L higher than the target
- For combined chlorine
  - More than a 0.5 – 1.0 mg/L increase should be avoided if possible.
- For FAA
  - probably around 0.2 mg/L within the plant
  - no more than 0.15 mg/L at the HSPS.

Adjusting the Process
Where to **START**

- If FAC > NH_2Cl target, then
  - Reduce the Cl_2 dose
- If NH_2Cl is too high, then
  - Reduce the NH_3 dose and
  - Reduce the Cl_2 dose
- If NH_3 is too high, either
  - Reduce the NH_3 dose or
  - Increase the Cl_2 dose

Adjusting the Process
Where to **START** (cont)

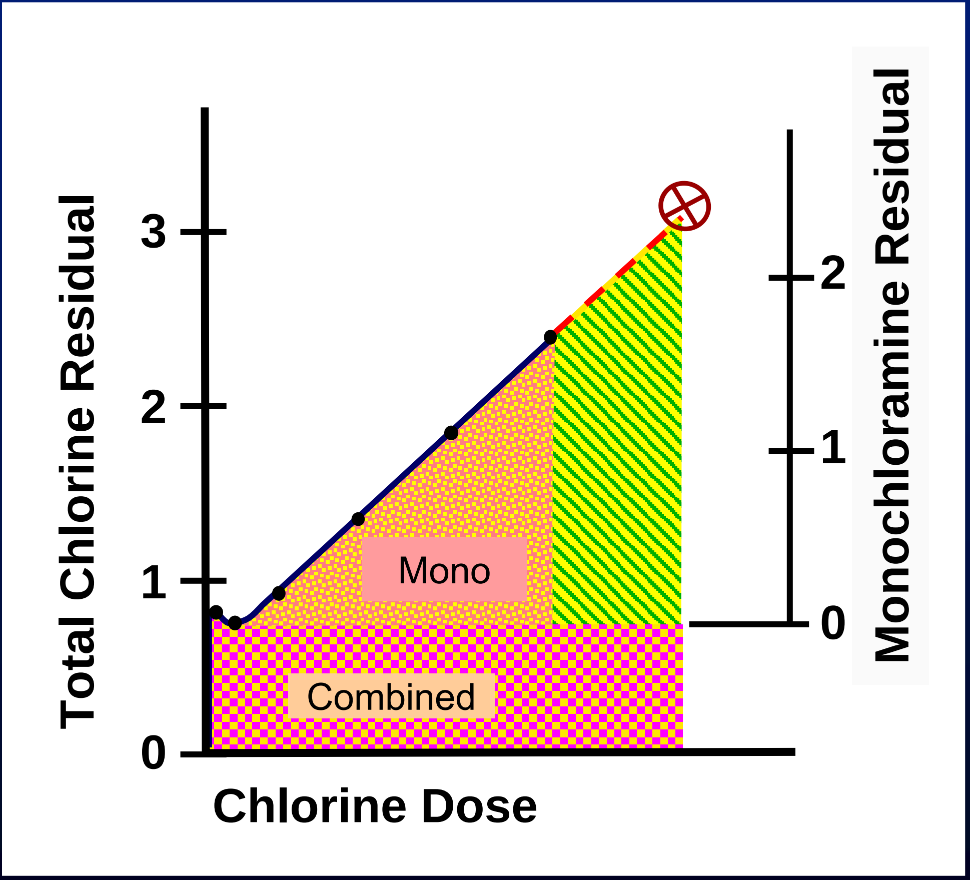
- If TAC dropped after Cl_2 addition, either
  - Increase the NH_3 dose or
  - Reduce the Cl_2 dose

- If combined chlorine increased, either
  - Increase the NH_3 dose or
  - Reduce the Cl_2 dose

IT'S A BALANCING ACT BASED ON WHERE THEY'RE AT ON THE BREAKPOINT CURVE

Back to the Scenario 2 Questions

- Q1: How much (if any) NH_3 is needed to reach our target?
- Q2: How much Cl_2 is needed?



The Situation:

- Data:
  - NH_3 was applied before Cl_2
  - NH_2Cl target = 2.3 mg/L
  - TAC = 2.3 mg/L
  - FAC = 0.0 mg/L
  - NH_2Cl = 1.6 mg/L
  - FAA = 0.2 mg/L as NH_3
  - 1.0 mg/L of FAC will produce 1.0 mg/L of mono (as Cl_2) so we need to add 0.7 mg/L of Cl_2
  - Based on a 1:1 molecular Cl_2: NH_3 ratio, the weight-based Cl_2: NH_3 ratio = 4.2:1

The Outcome:

- Calculations:

$$\frac{0.7\ \cancel{mg\ Cl_2}}{L} \times \frac{mg\ NH_3}{4.2\ \cancel{mg\ Cl_2}} = \frac{0.17\ mg\ NH_3}{L}$$

- After the adding 0.7 mg/L of Cl_2
  - TAC does not change from 2.3 mg/L
  - FAC remains at 0.0 mg/L
  - NH_2Cl increases (from 1.6) to 2.3 mg/L
  - FAA drops (from 0.20 mg/L) to 0.03 mg/L as NH_3

What's the Bottom Line?

1) Effective Process Control is more than just complying with regulatory monitoring requirements

2) Effective Process Control is a continuous multi-step process that involves:
   a) Collecting Data
   b) Evaluating Data against performance targets
   c) Making Appropriate Adjustments

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