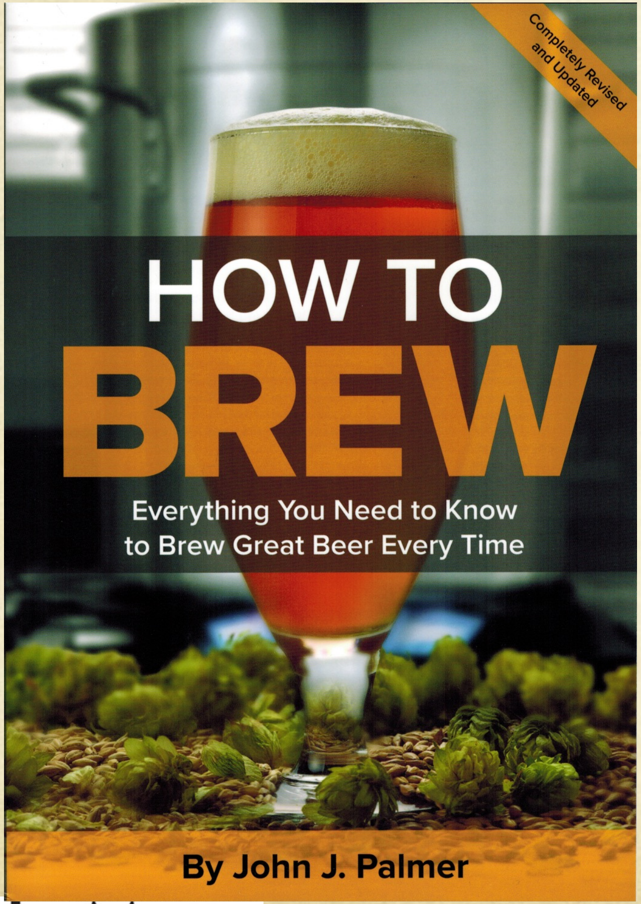
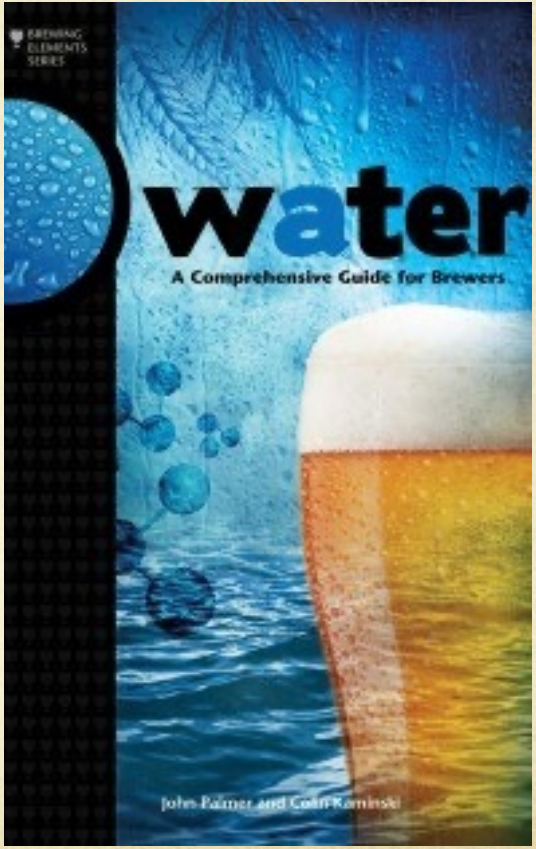
Deep Dive with Brewing Water

BYO Online Bootcamp
March 2023

John Palmer
Palmer Brewing Solutions, Inc.
In Association with
The LaMotte Company

Author of :





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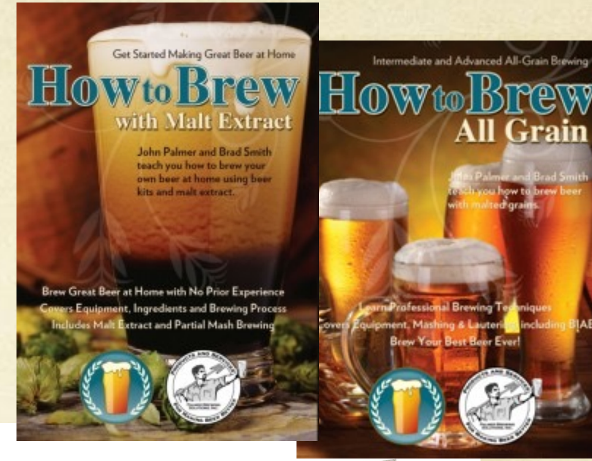

ANVIL
BREWING EQUIPMENT

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The Dogma of Virgin Water

- Brewers don't brew with water as-is.
- Classic beer styles may start out as a marriage of local ingredients and local water, but the beer/process evolves.
- Water has been adjusted for hundreds of years:
  - Pre-boiled to precipitate alkalinity (aka. temporary hardness).
  - Acid additions, sauermalz additions, salt additions.
  - Even changing the water source.

The BIG Picture

- Why do we adjust brewing water?
  - Mash pH – To Improve Beer Yield.
  - Mineral Levels – To Improve Beer Flavor.
- What do we adjust?
  - Mineral composition: Ca, Mg, HCO_3, SO_4, Na, Cl
- How do we adjust it?
  - Salt additions
  - Acid additions
  - Ion Removal (Ion-Exchange, Reverse Osmosis)

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How Water Affects Beer Flavor

- Water Residual Alkalinity drives Mash pH,
  Mash pH drives Beer pH,
  Beer pH drives beer flavor expression.

- Seasoning Balance: Sulfate to Chloride Ratio
  - More Sulfate = drier, more assertive hops
  - More Chloride = rounder, fuller, sweeter malt

- Amount of Seasoning (Total Dissolved Solids)
  - TDS is proportional to calcium salt concentrations…

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When do we adjust it?

- "The key point for control of pH throughout the brewing process is during mashing. This is due to the major influence that can be exerted at this stage on the content and format of the buffer systems that will operate subsequently in the wort and beer."
  - Taylor, D.G., The Importance of pH Control during Brewing, *MBAA Tech. Quart.* 27:131-136, 1990.

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Top 5 List for Brewing Great Beer

1. Sanitize everything.
2. Control the Fermentation Temperature.
3. Plenty of Clean, Healthy Yeast
4. Sufficient Boil
5. A Good Recipe
6. Water Adjustment

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Key Concepts for Water Adjustment

1. Beer and Brewing is Food and Cooking.
2. Know Your Source Water.
3. Residual Alkalinity is the cornerstone of Mash pH.
4. The Mash pH is the Equilibrium between the Water Chemistry and the Malt Chemistry.
5. The Mash pH is the cornerstone of Beer pH.
6. Beer pH controls beer flavor.

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1. Beer and Brewing is Food and Cooking

- Food at the wrong pH is boring or strange.
- Food without salt is bland, but don't over-salt your food!
- The mineral profile in the brewing water is the seasoning in beer.
- pH first, seasoning second.

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The Spaghetti Sauce Example

- If pH is too basic: It's rich but dull, boring.
- If the pH is too acidic: It's bright but not rich, one dimensional.
- If pH just right: Bright, Rich, Complex flavors.
- Once the pH is right, season to taste.
- *This is how you need to think about your beer.*

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Brewmaster as Chef

- To brew the best beer:
- Beer pH controls the expression of flavors.
  - Lower pH = Focuses Flavor, sharper
  - Higher pH = Broader Flavor, rounder
- The mineral profile of the water is the seasoning.
  - Relative Proportions – Sulfate to Chloride Ratio
  - Relative Levels – Mineral Structure

2. Know Your Source Water

- Surface Water
  - Lakes, Rivers, Reservoirs
- Ground Water
  - Aquifers, Springs, Wells, etc.
- Both
  - Water company will switch sources throughout the year, depending on availability and costs.

Source Water- Surface

- Surface Water
  - Lakes, Rivers, Reservoirs
  - Low in Minerals, High in Organics
  - Often requires Carbon Filtration to remove odors
  - Easy to add salts for alkalinity and flavor adjustment.

Source Water – Ground

- Ground Water
  - Aquifers: Limestone, Sandstone, Etc
  - Usually high in dissolved minerals and Alkalinity
  - Usually low in Organics
  - Often requires ion-exchange or RO to reduce Alkalinity

What is Water Hardness?

- Hardness = The sum of Calcium and Magnesium *measured as calcium carbonate*
  - We WANT calcium and magnesium in our mash/beer.
  - Water Hardness helps lower mash pH
  - Permanent Hardness = Ca/Mg Sulfates & Chlorides
  - Temporary Hardness = Ca/Mg Bicarbonate, Carbonate
  - SOFT = Not Hard.

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What is Alkalinity?

- Total Alkalinity = the sum of carbonate species in water (from limestone)
  - <u>Alkalinity ≅ Temporary Hardness</u>
  - This is why we say we want to get rid of temporary hardness.
  - Alkalinity raises Mash pH, makes beer less acidic, but duller.
    - High mash/wort pH promotes Astringency.

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Typical Surface Water

- Everything is below 50 ppm.
- Low Hardness
- Low Alkalinity
- Essentially distilled.

Mineral	(ppm)
Calcium (Calcium Hardness as $CaCO_3$)	7 (18)
Magnesium (Magnesium Hardness as $CaCO_3$)	1 (4)
Bicarbonate (Total Alkalinity as $CaCO_3$)	36 (30)
Sulfate	13
Chloride	14
Sodium	20

Typical Ground Water

- Low Hardness
- High Alkalinity
- Salts or acid additions can work for most gold/amber and darker styles.
- This water will cause scale in the HLT and piping.

Mineral	(ppm)
Calcium (Calcium Hardness as $CaCO_3$)	40 (100)
Magnesium (Magnesium Hardness as $CaCO_3$)	5 (21)
Bicarbonate (Total Alkalinity as $CaCO_3$)	144 (120)
Sulfate	27
Chloride	20
Sodium	25

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Atypical Ground Water

(Madison WI)

- Problem Alkalinity!
- Medium Hardness
- Low Sulfate, Chloride, Sodium
- Acid treatment to neutralize alkalinity to zero with lactic acid would add ~500 ppm of lactate ion (above taste threshold).

Mineral	(ppm)
Calcium (Calcium Hardness as $CaCO_3$)	58 (18)
Magnesium (Magnesium Hardness as $CaCO_3$)	31 (4)
Bicarbonate (Total Alkalinity as $CaCO_3$)	348 (285)
Sulfate	6
Chloride	3
Sodium	3

Water Source Comparison

Source	Calcium	Magnesium	Total Alkalinity	Sulfate	Chloride	Sodium	Silica	TDS
Seattle	8	1	22	1	4	2	5	43
Mississippi River	41	25	180	15	23	12	9	280
Lake Michigan	37	12	108	23	15	9	3	172
San Diego, CA	40	18	100	115	86	71	27	480
Lafeyette, IN	100	30	275	70	45	25	30	575
Guelph, ON	100	35	260	100	100	50	35	645

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What is "As $CaCO_3$"?

- Calcium Carbonate is limestone.
- It is the major source of hardness, alkalinity, and <u>scale</u> on plumbing.
- Therefore, Hardness (Ca^{+2}, Mg^{+2}) and Alkalinity (HCO_3^{-1}, CO_3^{-2}) are measured in terms of their <u>equivalents</u> "as $CaCO_3$"
- Eqivalent Wt. is Molecular Wt./valence

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Measuring Concentration as $CaCO_3$

- The equivalent weight of $CaCO_3$ is 50 g/Eq.
- Calcium, magnesium, and bicarbonate can be measured as themselves, i.e., Ca^{+2} 40 ppm
- Or they can be measured as their calcium carbonate potential, i.e., “as $CaCO_3$.
- 40 ppm Ca = 40/20 x 50 = 100 ppm Calcium Hardness as $CaCO_3$

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Source Water Treatment

- Carbon Filtration
  - Always a good first step
  - Removes residual chlorine/chloramine
  - Removes organic chemicals and odors
  - Often used in conjunction with Ultra-violet Light
- Alkalinity Reduction (Recommended)
  - Acidification – Neutralizes alkalinity, adds acid anion
  - Ion-exchange – Selective removal of ions *(Softening)*
  - Reverse Osmosis – Strip, then rebuild

Alkalinity Reduction for Brewing

- Calcium Carbonate scale is a pain in the ass.
- People tackle the problem by removing hardness and replacing with Sodium, ie., water softening.
- Remove the alkalinity instead!
  - No carbonate = no scale!
  - Anion softening
  - Reverse Osmosis
- Solves many brewing problems: scale, mash pH, etc.

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Water, in general:

- The important ions:
  - Calcium, Magnesium, Bicarbonate
  - Sulfate, Chloride, Sodium
- Ion Concentrations
  - 0-50 ppm is Low
  - 50-100 ppm is Medium
  - 100-150 ppm is High
  - **>150** ppm is a **Problem**

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Calcium

- The most important ion in brewing.
- Cofactor for:
  - Mash pH via Residual Alkalinity
  - Protein coagulation, trub formation.
  - Yeast metabolism, flocculation, and beer clarity
  - Oxalate Precipitation
- 50 ppm minimum in the wort for beer clarity
- 100-150 ppm in mash and sparge liquor for stable pH during lautering and better clarity.
- >200 ppm tends to taste minerally.

Magnesium

- The sidekick to calcium, but half as effective due to higher solubility of magnesium phosphates.
- A vital yeast nutrient.
  - 5 ppm minimum in the wort needed for yeast.
  - All malt wort (1.040, 10°P) typically has 70 ppm
- Recommended level in water is 0-40 ppm
  - >80 ppm tastes sour/bitter in beer
  - Dark beers seem to benefit from ~30 ppm in the mash.

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Total Alkalinity as $CaCO_3$

- The Villain
  - Keeps the Hero in check
  - Generally should be low, but RA is the key.
  - Bicarbonate is generally 95% of Total Alkalinity
- Alkalinity drives mash pH up
  - Causes more tannin and silicate extraction
  - Results in coarser bitterness from hops
  - But, provides balance for darker, more acidic grainbills
- Recommended range 0-120 ppm as $CaCO_3$, 200 ppm max.

Sulfate

- The Dark Hero.
  - Accentuates hop character, helps dry the beer finish.
  - Tastes minerally with high concentrations of sodium, chloride, and bicarbonate.
- 100-300 ppm in Pale Ales and IPAs improves hop character and finish.
  - Sulfur is generally not desired for German lagers such as Pilsner or Helles, conflicts with soft noble hop character. (≤50 ppm)
- Recommended range is 50-200 ppm for most styles.

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Chloride

- Imparts a rounder, sweeter, fuller quality to the beer.
- Minimum effective level for accentuating beer mouthfeel and flavor is probably 50 ppm.
- High Concentrations can hurt the beer:
  - >300 ppm can hurt clarity and stability
  - >400 ppm can hurt beer flavor
  - >500 ppm can hurt fermentation
- Recommended range is 50-150 ppm for most styles.

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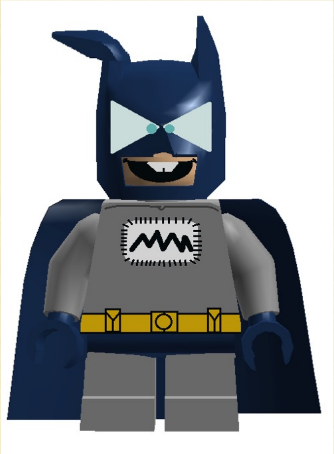
Sodium

- The bastard stepchild of brewing minerals.
  - It's everywhere: sodium chloride, sodium bicarbonate, sodium hydroxide…
  - Can be difficult to remove from water; reverse osmosis removes up to 97%.



- Recommended level is <100 ppm
  - Acts to improve mouthfeel and sweetness of malt.
  - >150 ppm tends to taste salty, especially with significant chloride (<100 ppm).
  - People's sensitivity varies.

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Total Dissolved Solids

- Total dissolved solids (TDS) is the sum of dissolved solids in water. The principal constituents are usually calcium, magnesium, sodium, potassium and carbonate, bicarbonate, chloride, sulfate, silica, and nitrate anions.
  - Typical range in brewing liquor: 100-600 ppm
- ~95% of those solids are the Ca, Mg, HCO3, SO4, Cl, and Na.
  - Nitrates, silica, potassium, iron, manganese, etc: ~1-10 ppm max.
- There is no direct test for Sodium, so we make use of the 95%, treating it as 100%, to solve for sodium using the other 5 ions: Ca, Mg, HCO3, SO4, Cl.

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Sulfate to Chloride Ratio

- Seasoning Effect: Dryness vs. Fullness
- It is not magic – 40:10 ≠ 400:100
- Useful range is 9:1 to 0.5:1
  - Maximum suggested sulfate is 500 ppm
  - Maximum suggested chloride is 200 ppm
  - Recommend to not exceed combined sum of 500 ppm. (Tastes Minerally)
    - IPA: 250 SO_4, 50 Cl
    - NEIPA: 150 Cl, 50 SO_4

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TDS Effect –Mineral Structure

- Light vs Heavy Seasoning
- Bohemian Pilsner
  - Rich, malty beer backed by large soft bitterness. Smooth finish balanced between malt and hops. No sharp edges.
- German Pils
  - Crisp and bitter hop forward character, followed by clean malt and dry finish. This is a beer defined by clean edges.
- Dortmunder Export
  - Balanced rich malt and firm dry bitterness. A "castle" of beer structure. Lower alcohol but doesn't taste like it.

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Comparison of Three Beers and Water Profiles

City	Ca^{+2}	Mg^{+2}	Na^{+1}	Cl^{-1}	SO_4^{-2}	HCO_3^{-1}	TDS
Pilsen	7	2	2	6	8	16	50
Munich*	12	17	4	8	18	95	150
Dortmund*	180	15	40	130	330	80	775

*Numbers after pre-boil decarbonation treatment.

- Orders of magnitude increase in total mineral levels (TDS).
- Transition of beer character from soft, to assertive, to bold.

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The Water pH is Not Important.

- The water pH is not important.
- The water pH is not important.
- The water pH is the chemical equilibrium of the water, i.e., the balance of hardness and alkalinity.
  - Higher = more alkalinity.
- Brewers are interested in the chemical equilibrium of the **<u>mash</u>**.

Know What's in Your Water

- Measure the Calcium, Magnesium, Total Alkalinity, Sodium, Chloride, Sulfate, and pH with the BrewLab by the LaMotte Company.

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Testing with the BrewLab, Part 1

1. Measure the Total Hardness as $CaCO_3$
2. Measure the Calcium Hardness as $CaCO_3$
   1. Subtract for Magnesium Hardness as $CaCO_3$
   2. Total Hdns = Ca Hdns + Mg Hdns
3. Measure Total Alkalinity as $CaCO_3$
   1. Calculate your Residual Alkalinity as $CaCO_3$
   2. RA = Total Alk – [(Ca Hdns + ½ Mg Hdns)/3.5]
4. Measure the Chloride (ppm)

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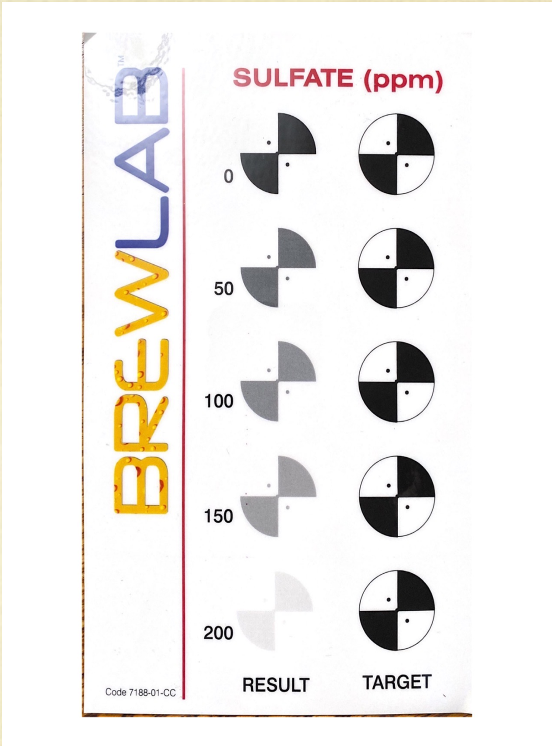
Testing with the BrewLab, Part 2

5. Estimate the Sulfate (visual test)
    1. It's a visual turbidity (cloudiness) test.
    2. Estimate how cloudy the test sample is compared to a gray scale of 50, 100, 150, 200, 250 ppm
    3. Visually, you can discern halves: i.e., 25 vs. 50 vs. 75 vs. 100
        1. MOST waters in the US are less than 100 ppm (Hazy).
        2. MANY are below 50 ppm (test looks Clear to Light Haze).
        3. This puts you in the ballpark, and that's close enough!
        4. You are simply trying to gauge your starting point; it doesn't have to be perfect. Is it 25, 50, 75, 100? Round up if you are not sure.



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Testing with the BrewLab, Part 3

- High Resolution is not necessary.
  - Dropper tests are +/- 10 ppm
  - Sulfate test is +/- 25 ppm

- Sodium is estimated by electrochemical balance, because the 6 ions should sum to zero, when concentrations are divided by equivalent weight. Ballpark is sufficient.

- $Ca_H/50 + Mg_H/50 + \mathbf{Na}/23 = (Alk)/50 + Cl/35 + SO_4/48$

$$\mathbf{Na} = 23 \times [Alk/50 + Cl/35 + SO_4/48] \div [Ca_H/50 + Mg_H/50]$$

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Ward Labs Report

Ca	38.5 ppm
Mg	8 ppm
T. Alk	215 ppm as $CaCO_3$
SO4-S	8 ppm
Cl	51 ppm
Na	78 ppm

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WARD
Laboratories, Inc.

Ag Testing - Consulting

Soil, Plant, & Water Program 2021 NAPT Participating Laboratory

Account No. : 68008

Water Analysis Report

[redacted]
NY [redacted]

Invoice No. : 1390787
Date Received : 12/05/2022
Date Reported : 12/06/2022

Lab Number : 29818

Results For : SHELDRAKE
Location :
Sample ID : SPRING WATER

pH	7.2
Total Dissolved Solids (TDS) Est, ppm	383
Electrical Conductivity, mmho/cm	0.64
Cations / Anions, me/L	6.1 / 6.4
	ppm
Sodium, Na	78
Potassium, K	2
Calcium, Ca	38.5
Magnesium, Mg	8
Total Hardness, $CaCO_3$	128
Nitrate, NO_3-N	1.4 (SAFE)
Sulfate, SO_4-S	8
Chloride, Cl	51
Carbonate, CO_3	< 1.0
Bicarbonate, HCO_3	262
Total Alkalinity, $CaCO_3$	215
Fluoride, F	0.15
Total Phosphorus, P	0.02
Total Iron, Fe	0.02

"<" - Not Detected / Below Detection Limit

Reviewed By : Raymond Ward 12/7/2022 Copy : 1 Page 1 of 2

Bus: 308-234-2418
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4007 Cherry Ave., P.O. Box 788
Kearney, Nebraska 68848-0788

What is the Difference: S vs SO_4?

- You will often see Sulfate on a water analysis listed as Sulfur, S.
  - This is an Equivalent measurement value.

- To convert Sulfur (S) to Sulfate (SO_4):
  - Divide by the equivalent weight of Sulfur, then multiply by the equivalent weight of Sulfate.

Example: 40 ppm as S = ? ppm as SO_4

Equivalent weight of S is 32/2 = <u>16</u>

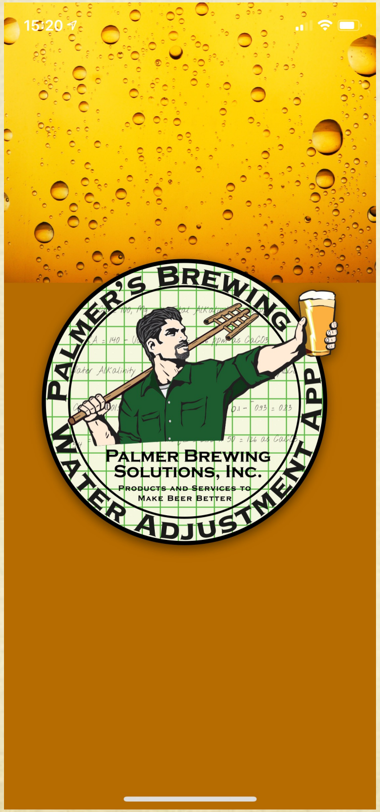
Equivalent weight of SO_4 is 96/2 = <u>48</u>

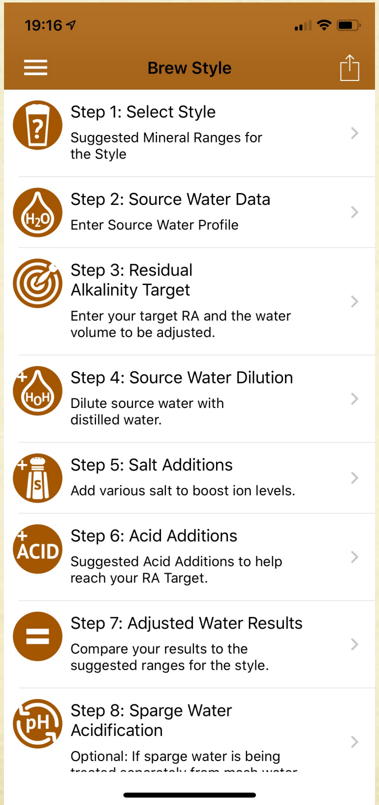
Therefore: 40 ppm/16 x 48 = 120 ppm as SO_4

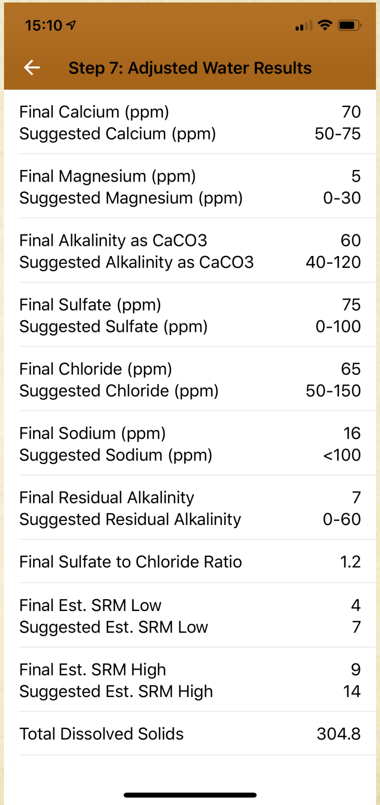
Bottom Line for SO_4 from S: Multiply by 3

The same applies for sodium and chloride given as saline (NaCl).

Palmer's Water App







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Using the Water App: Steps 1-3

19:18

Step 1: Select Style

Brew Style Not Selected	Change
Calcium (ppm)	
Magnesium (ppm)	
Alkalinity as CaCO3	
Sulfate (ppm)	
Chloride (ppm)	
Sodium (ppm)	
Residual Alkalinity	
Color (SRM)	

14:48

Step 1: Select Style

3B. Oktoberfest/Marzen	Change
Calcium (ppm)	50-75
Magnesium (ppm)	0-30
Alkalinity as CaCO3	40-120
Sulfate (ppm)	0-100
Chloride (ppm)	50-150
Sodium (ppm)	<100
Residual Alkalinity	0-60
Color (SRM)	7-14

14:50

Step 2: Source Water...

Source Water	BrewLab® Data
Calcium (ppm)	40.0
Magnesium (ppm)	10.0
Choose Bicarbonate or Alkalinity	Alkalinity as CaCO3
Alkalinity as CaCO3	120.0
Sulfate (ppm)	40.0
Chloride (ppm)	35.0
Sodium (ppm)	32.0
Water pH	8.0
Source Data Diagnostics	
Cation Sum	4.2
Anion Sum	4.2
Residual Alkalinity as CaCO3	86
Sulfate to Chloride ratio	1.1
Est SRM Low	17
Est SRM High	33

14:52

Step 3: Residual Alkalinity Target

Input Data	
Target Residual Alkalinity	25
Water Input Unit	gallons
Mash Water Volume	8.0
Output Data	
Alkalinity to be Reduced	61
Additional Alkalinity Needed	0
Target RA Est. SRM (Low)	6
Target RA Est. SRM (High)	12

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Using the Water App: Steps 4-7

Step 4: Source Water Dilution

14:57

Input Data

Dilution Rate (0% is undiluted, 100% is all distilled.)	50

Output Data

Calcium (ppm)	20
Magnesium (ppm)	5
Total Alkalinity as CaCO3	60
Sulfate (ppm)	20
Chloride (ppm)	17
Sodium (ppm)	16
Volume of Source Water	4.0
Volume of Distilled Water	4.0
Alkalinity to be Reduced	18
Additional Alkalinity Needed	0
Adjusted Residual Alkalinity as CaCO3	43
Adjusted Sulfate to Chloride Ratio	1.1

Step 5: Salt Additions

15:01

Salt Additions (grams)

Gypsum CaSO4 *2H2O	3
Calcium Chloride CaCl2*2H2O	3
Epsom Salt MgSO4 *7H2O	0
Calcium Hydroxide Ca(OH)2	0
Baking Soda NaHCO3	0
Canning Salt NaCl	0

Salt Contributions (ppm)

Calcium (ppm)	50
Magnesium (ppm)	0
Alkalinity from Hydroxide	0
Alkalinity from Bicarbonate	0
Sulfate (ppm)	55
Chloride (ppm)	48
Sodium (ppm)	0
Adjusted Residual Alkalinity as CaCO3	7
Adjusted Sulfate to Chloride Ratio	1.2

Step 6: Acid Additions

15:04

Input Data

Select Acid	88% Lactic
Mash Water Addition (ml)	0.0

Output Data

Est. Acid Addition (ml)	0.0
Alkalinity Reduced (as CaCO3)	0
Anion Contribution (ppm)	0.0

Step 7: Adjusted Water Results

15:10

Final Calcium (ppm) Suggested Calcium (ppm)	70 50-75
Final Magnesium (ppm) Suggested Magnesium (ppm)	5 0-30
Final Alkalinity as CaCO3 Suggested Alkalinity as CaCO3	60 40-120
Final Sulfate (ppm) Suggested Sulfate (ppm)	75 0-100
Final Chloride (ppm) Suggested Chloride (ppm)	65 50-150
Final Sodium (ppm) Suggested Sodium (ppm)	16 <100
Final Residual Alkalinity Suggested Residual Alkalinity	7 0-60
Final Sulfate to Chloride Ratio	1.2
Final Est. SRM Low Suggested Est. SRM Low	4 7
Final Est. SRM High Suggested Est. SRM High	9 14
Total Dissolved Solids	304.8

25?

(Add 1g baking soda)

3. Residual Alkalinity is the Cornerstone for Establishing Mash pH

- Water alkalinity raises mash pH above the (normal) distilled water value.
- High mash pH typically leads to high wort pH, coarse/harsh bitterness, and high beer pH.
- Residual Alkalinity is the most important parameter for understanding the effects of water chemistry in the mash and beer.

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What is Residual Alkalinity?

- Residual alkalinity is the difference between effects of the Total Alkalinity and Hardness on mash pH.
  - RA = Total Alkalinity – (Ca + ½ Mg)/3.5
    Note: Units must be mEq/L or ppm as $CaCO_3$
    3.5 factor is dependent on Mash Ratio and Crush
- Calcium and Magnesium react with malt phosphates to produce protons and lower mash pH.
  - $10Ca^{+2} + 12HCO_3^{-1} + 6H_2PO_4^{-1} + 2H_2O \rightarrow$

    $Ca_{10}(PO_4)_6(OH)_2 + 12CO_2 + 12H_2O + 2H^{+1}$
  - Magnesium also reacts, but about half as much.

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Effect of RA on baseline Mash pH

- The distilled water mash pH of a base malt is typically 5.6-6.0. (Distilled water is the baseline.)
- Therefore, achieving the optimum mash pH range (5.2-5.6) with base malt alone is problematic.
- The RA of water can raise the mash pH by 0.1 pH unit per ~75 ppm as $CaCO_3$ RA (or 1.5 mEq/L).
- Conversely, negative RA values can lower the mash pH by almost the same amount.
- <u>This is why we typically want to add hardness and remove alkalinity from our brewing water.</u>

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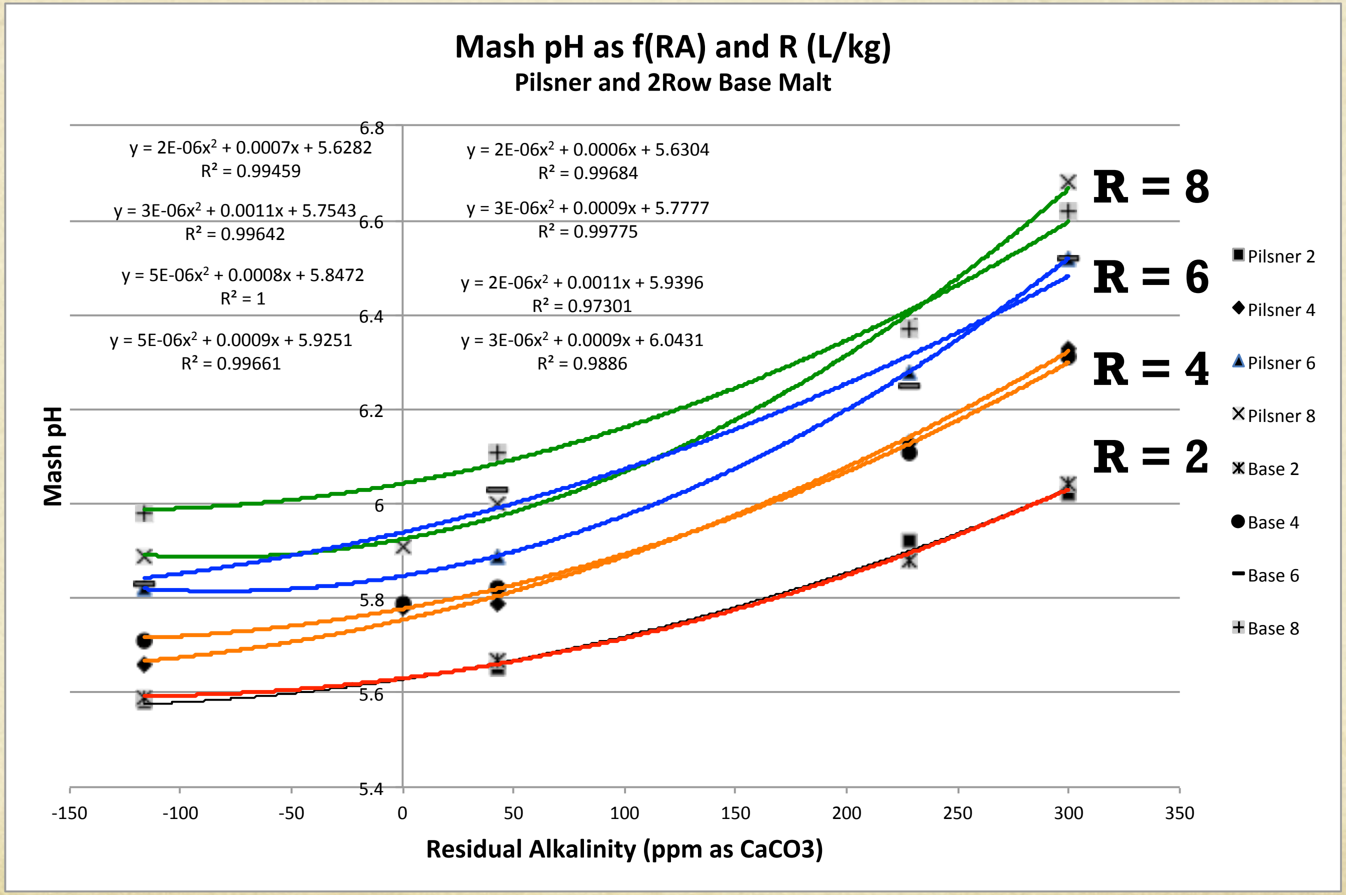
RA has Increasing Effects



4. Mash ph is the Equilibrium between Water Chemistry and Malt Chemistry

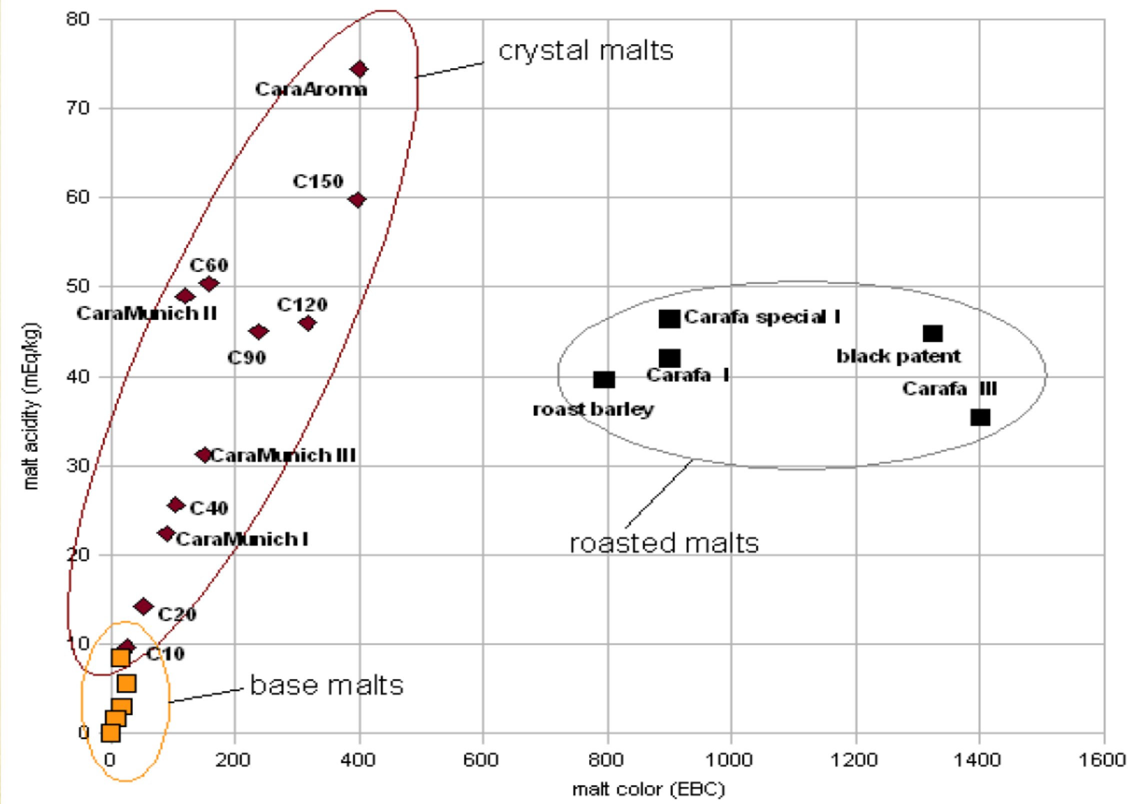
- The effect of water chemistry in the mash is summarized by Residual Alkalinity.
  - But this is only half the story.
- Each Malt contributes (poly)peptide buffers and organic acids.
  - Quantifiable by titration and distilled water mash pH
  - Malt acidity is variable between maltsters and crop year, even for the same type.

Malt Chemistry

- Specialty malts have been kilned and/or roasted to produce color (melanoidins) and flavor compounds.
- These Maillard reactions also produce organic acids, such as acetic acid.
- There is a transition from yellow-red melanoidins to brown melanoidins at 325-350°F (165-175°C).
- This is also the transition for kilning to roasting.

Kilned vs. Roasted Acidity

- Kilned malts seem to follow a linear trend.
- Roasted malts appear to be clumped.



From K. Troester,
www.braukaiser.com

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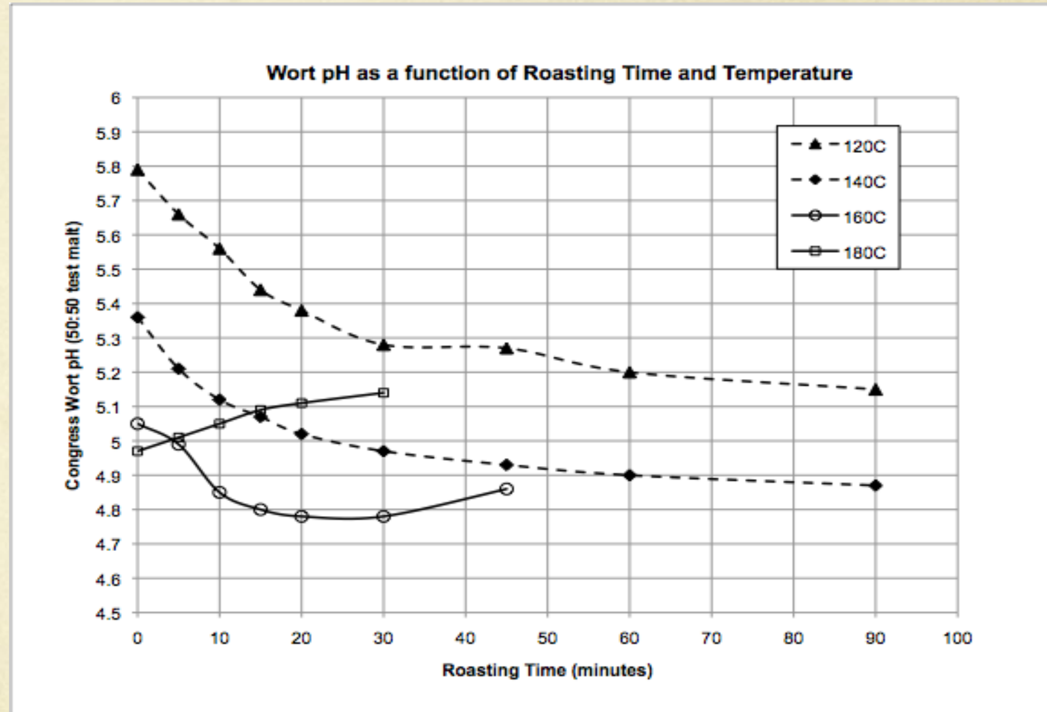
Kilned vs. Roasted Acidity

- Basically, malt acidity peaks as a function of malt color.
- The highest colored Kilned malts are the most acidic.
- Roasted malt acidity tends to decrease with increasing color (roasting time).



Data from Vandecan, S., et al. "Formation of Flavor, Color, and Reducing Power During the Production Process of Dark Specialty Malts," ASBC 69(3):150-157, 2011.

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Coming Together in the Mash

- Let's assume our target mash pH is 5.4.
- The base malt, at a DI water pH of 5.8, is *alkaline* and needs to come down.
- The specialty malt(s), at a DI water pH of (4.6), is *acidic* and needs to come up.
- The residual alkalinity of the water can be positive or negative, and may help or hinder reaching the target.

Estimating Mash pH

Base Malt Alkalinity x Weight

+

Specialty Malt Acidity x Weight

+

Water Residual Alkalinity x Volume

=

Target Mash pH (+/– a bit*)

*can be adjusted with strong acid or base

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Bottom Line

Water Chemistry

+

Malt Chemistry

=

Mash Chemistry
(measured as pH)

End of First Half

<final Jeopardy music>

Break

- Mini-Mashes to test different grainbills and waters and resultant mash pH.
- 4 waters: Pale Hoppy, Pale Malty, Amber Malty, Dark Malty
- 3 grain bills:
  - Base
  - Base and 10% Crystal
  - Base, 10% Crystal, 10% Roast

Suggested Salt Additions to RO Water (grams per gallon)

Beer	$CaSO_4$	$CaCl_2$	Baking Soda	Ca	Na	SO4	Cl	HCO_3	RA
Pale Hoppy	1	0.5	0	98	0	147	64	0	-70
Pale Balanced	0.75	0.75	0	100	0	111	96	0	-72
Pale Malty	0.5	1	0	103	0	74	127	0	-73
Amber Hoppy	1	0.5	0.5	98	36	147	64	95	+8
Amber Balanced	0.75	0.75	0.5	100	36	111	96	95	+6
Amber Malty	0.5	1	0.5	103	36	74	127	95	+4
Dark Hoppy	1	0.5	1	98	72	147	64	190	+86
Dark Balanced	0.75	0.75	1	100	72	111	96	190	+84
Dark Malty	0.5	1	1	103	72	74	127	190	+82

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Sidebar: What is pH?

- It is the concentration and activity of hydrogen ions in solution.
- *But, it is also a measure of chemical equilibrium.*
- A good analogy is Noise, measured as decibels.
  - You can monitor a process or group of children in the next room simply by paying attention to the noise level.
  - If you want to be serious about controlling your beer, you need to measure pH.

Testing pH

- A good pH meter will give an accurate reading in about 15 seconds.
- Brewers want to differentiate between 0.1 pH units, therefore you need a meter with a resolution of 0.01.
- Every pH electrode typically has a useful life of 1-3 years if well maintained. After that, they tend to drift and are hard to calibrate.

LaMotte Order Code No. 1741

https://www.amazon.com/dp/B00BT145XW/ref=cm_sw_em_r_mt_dp_B29VJ7DMS7J4B1P4MNN9

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pH and ATC

- Most modern pH meters have automatic temperature compensation (ATC).
- The purpose of ATC is to be able to measure a sample at a *different temperature* than the calibration temperature, and give an accurate reading of the pH *at that different temperature*.
    - i.e., it maintains calibration
- It does not compensate for the actual pH change of the solution due to temperature.

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pH Changes with Temperature

- The pH of a solution will change with temperature, due to changes in activity (energy) and buffer response.
- Different worts (styles) will have different activities and different pH changes as a function of temperature.
- Generally, wort pH lowers by ~0.3 between room (20°C) and mashout temperature (75°C).
  - We use room temperature as a common standard for comparison. (ASBC MOA Beer-9, pH)

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Mini-mash pH Results

	Pale Hoppy RA = -70	Pale Malty RA = -70	Amber Malty RA = +5	Dark Malty RA = +80	*Delta*
Pale	**5.7**	**5.6**	**5.8**	**6.3**	*0.6*
Amber	**5.6**	--	--	**6.1**	*0.5*
Dark	**5.3**	**5.3**	**5.6**	**5.9**	*0.6*
delta	*0.4*	*0.3*	*0.3*	*0.4*	

3 grain bills:

- Pale: Base malt
- Amber: Base and 10% Crystal
- Dark: Base, 10% Crystal, 10% Roast
- Rv = 4 L/kg (2 qts./lbs.)

5. The Mash pH Sets Up the Beer pH

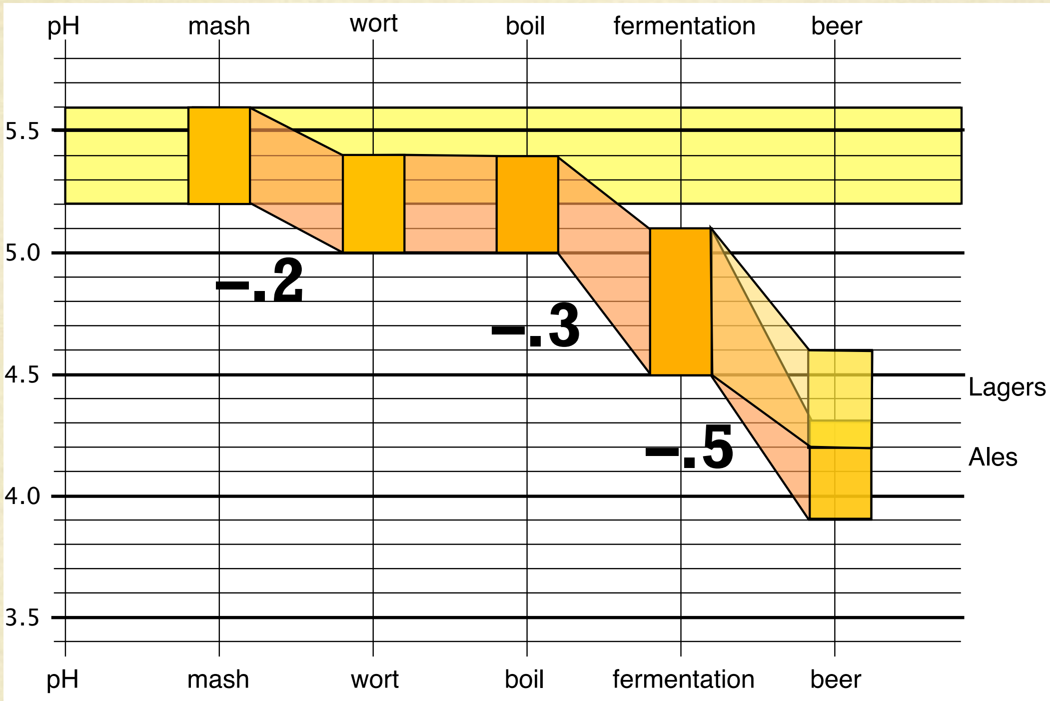
- "The key point for control of pH throughout the brewing process is during mashing. This is due to the major influence that can be exerted at this stage on the content and format of the buffer systems that will operate subsequently in the wort and beer."
  - Taylor, D.G., The Importance of pH Control during Brewing, *MBAA Tech. Quart.* 27:131-136, 1990.

pH progression

1. Residual Alkalinity is the cornerstone of Mash pH.
2. The Mash pH is the Equilibrium between the Water Chemistry and the Malt Chemistry.
3. The Mash pH sets up the wort pH.
4. The wort pH sets up the beer pH.
5. The beer pH controls how the beer flavors are experienced by your palate.

Mash pH Sets Up Beer pH

5.2-5.6



Typically 4.0-4.6 Style/recipe dependent

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What Does the Mash pH Do?

- The enzymatic processes in the mash are controlled by temperature and pH.
- Enzymes typically perform best in a bell-shaped curve about their temperature and pH optima.
  - Enzymes can be denatured by high temperatures
  - Enzymes can be denatured by high and low pH
- Therefore, having a mash pH that is too high or too low can negatively impact starch conversion, soluble and total nitrogen, lauterability, fermentability, and yield.

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What Is the Optimum pH?

- It Depends:
  - There are many enzymatic processes occurring in the mash, each with it's own optimum pH range.
  - The pH optima for proteolysis is lower than for saccharification.
- Therefore optimum mash pH represents a compromise between priorities: conversion, FAN, lauterability, etc.
  - "Optimum" Mash pH is generally based on optimum <u>yield.</u>
  - However, published opinions differ on what the optimum range is…

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pH for Best Yield, by Author

	Mash Temp	Room Temp
Briggs et al.:	5.2-5.4	(5.45-5.65 at 20°C)
Bamforth et al.:	5.3-5.8	(5.55-6.05 at 20°C)
Kunze:	(5.25-5.35)	5.5-5.6 at 20°C

- Best Yield is therefore 5.5-6.0
  - But pH >5.8 promotes astringency!
- Anecdotally, many brewers report better beer flavor with lower mash pH, 5.2-5.6 at 20°C.
  - Parentheses indicate pH/temperature conversion

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Bottom Line on pH Optima

- There is no single correct answer, it is a range where your target will depend on several factors, including water profile, grain bill, yield targets, and perceived beer flavor.
- I recommend picking a value between 5.2-5.6 (measured at room temperature) that best suits your beer recipe.
  - Mash pH should be 5.2-5.6 (paler = lower)
  - Don’t go over 5.8 or under 5.2!
  - Beer pH should be 4.0-4.4 (paler = lower)

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WHEN & HOW to Measure pH?

- You are looking for a mash pH of 5.2-5.6 @ room temp, <u>for saccharification</u>.
- Measure the pH about 10 minutes into the mash.
- Cool the mash wort sample to room temp on a shallow dish, then measure with a pH meter.
- *Note that the mash pH decreases during the mash.*
- If at first you don't succeed, brew again. (you can try to fix it now, but conversion happens quickly, so…)

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Effect of <u>Beer pH</u> on Flavor

- In general, a lower beer pH focuses and brightens the malt and hop flavors.
  - Better for single-malt pale beers.
  - Dark beers can become a singular “roast” character.
- In general, a higher beer pH broadens and opens up malt and hop flavors.
  - Better for multiple-malt dark beers.
  - Pale beers can become dull and harsh.

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C. Kaminski's Observations on pH
American Pale Ale

- Boil pH and influence on Hop expression:
  - 5.4 – Strong and Harsh
  - 5.2 – Full and Rich
  - 5.0 – Dull and Flaccid
- Beer pH and Flavor of Pale Ales
  - 4.4 – Soft and Soapy
  - 4.2 – Normal
  - 4.0 – Sharp and Crisp

Optimizing Beer pH

- Every beer recipe has an optimum beer pH, generally in the range of 4.0-4.6.
- Every beer should have a flavor portfolio that includes:
  - malt flavors and aromas,
  - hop flavors and aromas,
  - yeast flavors and aromas.
- If you can't taste or smell *everything*, you are probably not at the optimum beer pH.

Beer pH and You

- Every beer recipe has an ideal pH, where its flavors are best expressed.
- That *particular* pH depends on the style and recipe, *i.e., water profile and grainbill*.
- The brewer's art is finding that particular pH, and maintaining it, batch to batch, season to season.
- Achieving that particular pH starts with the water chemistry, and mash pH.

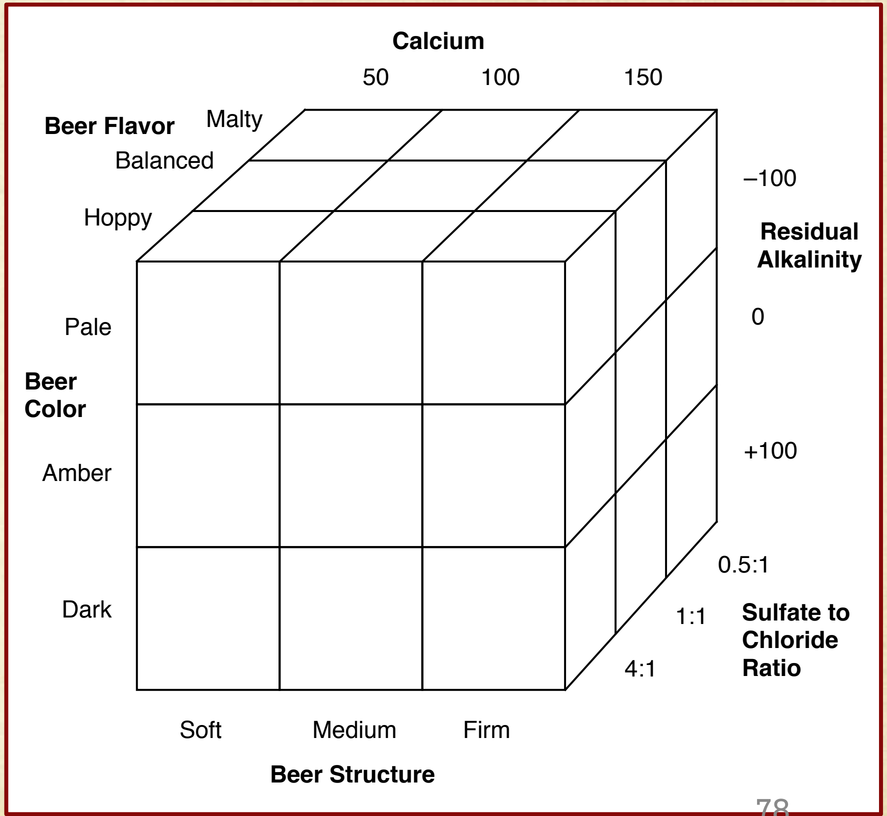
Why Do We Adjust Water?

1. **To Hit our Mash pH Target!**
   a. **Better mash = better wort = better beer**

2. To Improve Beer Flavor
   a. Flavor expression (pH)
   b. Flavor Balance (Sulfate:Chloride)
   c. Flavor Structure (TDS)

Adjusting Water for Style Summary

- To Adjust water for style, use the cube:
  - Define the style by Flavor, Color, & Structure.
  - Read water profile by Calcium, Total Alkalinity, and Sulfate to Chloride Ratio.
    - Beer Color => Residual Alkalinity
    - Flavor Balance => Sulfate to Chloride
    - Beer Structure => Calcium level



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Suggested Salt Additions to RO Water

(grams per gallon)

Beer	$CaSO_4$	$CaCl_2$	Baking Soda	Ca	Na	SO4	Cl	HCO_3	RA
Pale Hoppy	1	0.5	0	98	0	147	64	0	-70
Pale Balanced	0.75	0.75	0	100	0	111	96	0	-72
Pale Malty	0.5	1	0	103	0	74	127	0	-73
Amber Hoppy	1	0.5	0.5	98	36	147	64	95	+8
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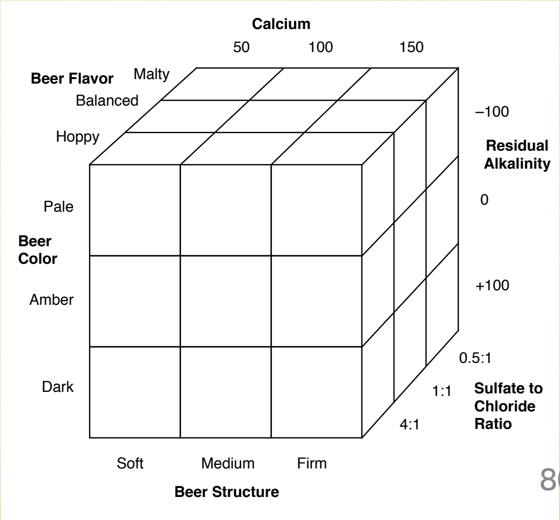
Dark Balanced	0.75	0.75	1	100	72	111	96	190	+84
Dark Malty	0.5	1	1	103	72	74	127	190	+82

How Do I Adjust Water for Beer Style?

Ca^{+2}	Mg^{+2}	Alk.	SO_4^{-2}	Cl^{-1}	Na^{+1}	Res. Alk.
40	10	120	40	35	32	86

1. What are the style characteristics that you want to brew?
   a) Color: Pale, Amber, or Dark?
   b) Flavor Balance: Malty, Balanced, or Hoppy?
   c) Structure: Soft, Medium, or Firm?



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How Do I Adjust Water for Beer Style?

Ca^{+2}	Mg^{+2}	Alk.	SO_4^{-2}	Cl^{-1}	Na^{+1}	Res. Alk.
40	10	120	40	35	32	86

3. Add Calcium based on:
   a) Structure (generally soft or medium) => 50-100 ppm
   b) Color/RA target => Calculate new RA after salt additions.

- For Pale, Hoppy, Medium:
  - Add 1 gram/gallon of calcium sulfate

Ca^{+2}	Mg^{+2}	Alk.	SO_4^{-2}	Cl^{-1}	Na^{+1}	Res. Alk.
102	10	120	187	35	32	42

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How Do I Adjust Water for Beer Style?

Ca^{+2}	Mg^{+2}	Alk.	SO_4^{-2}	Cl^{-1}	Na^{+1}	Res. Alk.
102	10	120	187	35	32	42

4. Recalculate RA after calcium salt addition:
   a) Does RA need to decrease (pale)? => Neutralize with acid.

- For Pale, Hoppy, Medium:
  - Add 0.75 ml per gallon of 88% Lactic Acid

Ca^{+2}	Mg^{+2}	Alk.	SO_4^{-2}	Cl^{-1}	Na^{+1}	Res. Alk.
102	10	3	187	35	32	–75

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How Do I Adjust Water for Beer Style?

Ca^{+2}	Mg^{+2}	Alk.	SO_4^{-2}	Cl^{-1}	Na^{+1}	Res. Alk.
102	10	3	187	35	32	-75

- Final Adjusted Water:
  1. Acidify to neutralize alkalinity first, then add calcium salts.
  2. Do a proportional mini-mash to verify mash pH target.

- When to add salts:
  - First priority is achieving your mash pH target.
  - Add most/all adjustments to HLT to achieve mash pH target.
  - Second priority is achieving Flavor Balance and Structure.
  - Add additional salts or acid as necessary to kettle for flavor.

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When to Add Salts?

- Mash pH is the thing!
- Add to HLT, or Mash, but get mash pH right.
- You can always add more at the kettle if you want to tweak total calcium or Sulfate:Chloride.
- You can do post adjustments, but more is needed than if done earlier in process.

Capping– Dark Grain Last?

- Mash Roast malt separately or together?
- Depends; the important thing is your mash pH.
- How much roast flavor do you want?
  - Shorter time = more grain
  - Longer time = less grain
  - pH determines flavor profile

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Acidification of Sparge Water

- Acidification of Brewing and/or Sparge water to near mash pH is common practice at many breweries.
- Phosphoric acid is most commonly used due to minimal flavor impact.
- Acidification can be done to a target pH, ex. 5.5, 5.7, or 6.0, depending on the need.
  - **Important to verify subsequent mash and wort pH!**
  - **Important to manage calcium levels.**

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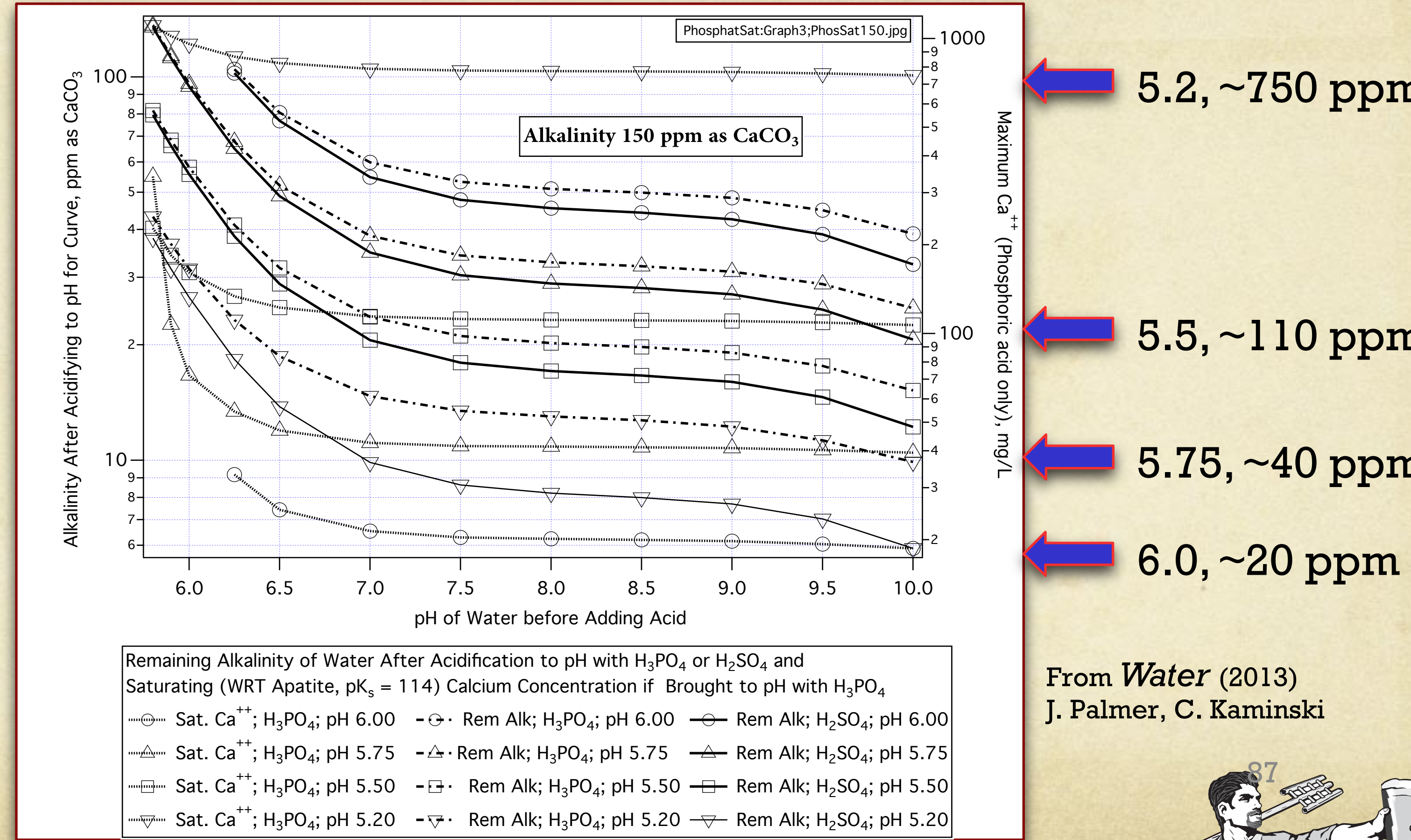
Calcium Loss Due to Phosphoric Acid



From *Water* (2013)
J. Palmer, C. Kaminski

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Key Concepts for Water Adjustment

1. Beer and Brewing is Food and Cooking.
2. Understand Your Water Source .
3. Residual Alkalinity is the cornerstone of Mash pH.
4. The Mash pH is the Equilibrium between the Water Chemistry and the Malt Chemistry.
5. The Mash pH is the cornerstone of Beer pH.

Water: The Final Adjustment

Order of Precedence for Great Beer

1. Sanitation
2. Fermentation Temperature Control
3. Yeast Pitching Rate
4. The Boil
5. Recipe Proportions
6. Water Adjustment

Theory? or Reality?

- You've read the books
- You've listened to the experts
- But what happens when you actually try it?
  - Thank goodness for Brulosophy…

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Brulosophy #1 – Dortmund Profile

- Brewed a German Pils
  - Tap water: 4 Ca, 1 Mg, 33 HCO3, 6 SO4, 2 CL, 10 Na, <u>24 RA</u>
  - Dortmund: 145 Ca, 24 Mg, -23 TA, 302 SO4, 99 Cl, <u>-140 RA</u>
- Mash pH
  - Tap: 5.6
  - Dortmund: 5.2

Brulosophy #1 - Dortmund

- Triangle Test, Significant: P = 0.014
  - 9/15 could differentiate the beers
  - Aroma: 6/9 preferred the treated beer
  - Flavor: 7/9 preferred the treated beer
  - Mouthfeel: 9/9 felt it was the same or similar
  - Overall: 6/9 preferred the treated beer
- Schott: “Considerably crisper and lighter on the palate, with sharp bitterness that balanced the malt well.”

Brulosophy #2 – SO4:Cl Ratio

- Irish Stout recipe brewed with 2 different waters
  - Pale Hoppy: 90 Ca, 16 Mg, 149 HCO3, 167 SO4, 67 Cl, 36 Na,
    - **2.5:1 SO4:Cl**
  - Dark Malty: 82 Ca, 11 Mg, 86 HCO3, 55 SO4, 123 Cl, 25 Na
    - **0.44:1 SO4:Cl**
  - Both mashes adjusted to 5.4 pH with lactic acid.

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Brulosophy #2 – SO4:Cl Ratio

- Triangle Test, Demonstrated: P = 0.001
  - 18/29 could differentiate the beers
  - 3/18 had no preference
  - 8/18 preferred the Dark Malty
  - 7/18 preferred the Pale Hoppy
  - Frazer: "Pale hoppy was unidimensional, DM was layered, more complex."

Brulosopy #3 – Post Ferm Adjustment

- Belgian Pale Ale recipe
  - OG 1.051
  - FG 1.012
- Calcium salt additions to the kegs
  - Beer A: 1:1 SO4:Cl
  - Beer B: 2:1 SO4:Cl

Brulosopy #3 – Post Ferm Adjustment

- Triangle Test, Demonstrated: P = 0.010
  - 12/21 could differentiate the beers
  - 4/12 had no preference
  - 6/12 preferred the 2:1
  - 2/12 preferred the 1:1
  - Schott: "2:1 was notably crisper…pleasingly cleaner palate. 1:1 (had) a rounded overall character."

Brulosopy #3b – Post Ferm Adjustment

- American Pale Ale recipe
  - OG 1.059
  - FG 1.009
- Gypsum additions to the kegs
  - Beer A: 92 Ca, 152 SO_4, 49 Cl
  - Beer B: 155 Ca, 306 SO_4, 49 Cl

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Brulosopy #3b – Post Ferm Adjustment

- Triangle Test, Not Demonstrated: P = 0.95
  - 12/21 Needed
  - 4/21 could differentiate the beers
  - Lovell: "2/5 correct. To my palate, the gypsum addition had no qualitative impact on these beers, they were the same."

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Brulosophy #4 – Phosphoric vs. Lactic Acids

- Acidifying source water with each acid to neutralize alkalinity and brew a Kolsch.
  - Water: 42 Ca, 12 Mg, 99 TA, 59 SO_4, 50 Cl, 27 Na, 62 RA
  - After Acid: 42 Ca, 12 Mg, -53 TA, 59 SO_4, 50 Cl, 27 Na, -90 RA
  - 7.2 ml 88% Lactic acid => 364 ppm lactate
    - about taste threshold
- Mash pH for both batches = 5.4

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Brulosophy #4 – Phosphoric vs. Lactic Acids

- Triangle Test, Not Demonstrated P = 0.11
  - 11/23 could differentiate the beers
  - 5/11 had no preference
  - 4/11 preferred the phosphoric
  - 1/11 preferred the lactic
  - Frazer: He could differentiate the beers as they warmed by smelling a butter character from the lactic acid. (paraphrasing)
  - To me, lactic acid smells like brown sugar.

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Brulosophy #5- Boil pH for IPA

- Premise – that higher boil pH increases hop utilization and could cause harsher beer.
- IPA at ~90 IBU, 1.066 OG
  - Wort A: 5.4
  - Wort B: 5.1
    - Phosphoric Acid (2.5 ml) added after the mash.

Brulosophy #5- Boil pH for IPA

Parameter	"High" pH	"Low" pH
Boil pH	5.4	5.1
Final Gravity	1.013	1.018*
Beer pH	4.5	4.4

(* I don't know why.)

- Triangle Test, Not Demonstrated: P = 0. 43
  - 15/42 could differentiate the beers
  - 8/15 preferred the low pH beer
  - 5/15 preferred the high pH beer
  - 2/15 no preference
- Frazer: "I slightly preferred the higher pH beer for more assertive bitterness, but not overly harsh."

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Brulosophy #6 – Sulfate to Chloride

- IPA: Ray's MACC IPA
  - OG/FG 1.065/1.005
- Water (no other details given)
  - A: 150:50 Sulfate to Chloride
  - B: 50:150 Sulfate to Chloride

Brulosophy #6 – Sulfate to Chloride

- Triangle Test, Demonstrated P = 0.003
  - 14/22 could differentiate the beers
  - 3/14 had no preference
  - 5/14 preferred the 50:150
  - 4/14 preferred the 150:50
  - 2/14 admitted they got lucky
  - Huolihan: "The high sulfate had a more assertive bitterness with a hop character that popped out…high chloride was smoother, mouth coating, and somewhat chalky/slick with a more muted hop character…"

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Brulosophy #7 – Low Mash pH

- Premise: Low mash pH (<5) should inhibit amylase enzymes.
- Beer Recipe:
  - 90% Pilsner malt, 10% Flaked Oats
  - OG 1.046, 32 IBU, Southern German Lager yeast
  - 50 Ca, 0 Mg, 16 HCO3, 50 SO4, 50 Cl, 8 Na, -22 RA
  - 19 ml Lactic Acid added to mash for <u>4.5 pH</u>
  - Other mash, no acid, <u>5.3 pH</u>

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Brulosophy #7 – Low Mash pH

- OG After Boil:
  - Normal pH=1.050, Low pH=1.054
  - Could be protein from oats, or normal variability
- FG:
  - Normal pH= 1.011, Low pH=1.017
  - Could be protein, or less fermentable wort…
- Only 7/22 picked the odd beer. P = 0.64
  - Difference not demonstrated.

Brulosophy #8 – Ratio vs. TDS

- Premise: Same beer, same SO4:Cl, different TDS
  - Medium versus Firm on Brew Cube.
- 200:100
  - OG= 1.050, FG= 1.010
- 50:25
  - OG=1.052, FG=1.012
- Probably normal variability for OG/FG

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Brulosophy #8 – Ratio vs. TDS

- 8/22 picked the odd beer.
  - Difference not demonstrated.
- This experiment does not support the premise of the brew cube: that Mineral Structure is a discernible difference.
- This experiment does support that ratio is more important than total concentration.

Brulosophy #9 – High Mash pH

- Premise: High Mash pH => High Boil pH => Astringency
- Water (built):
  - Mash pH 5.2: **95 Ca,** 0 Mg, 0 HCO3, 104 SO4, 93 Cl, **RA~ -150**
    - Lactic Acid
  - Mash pH 6.4: **201 Ca,** 0 Mg, **~300 TA,** 104 SO4, 93 Cl, **RA~ +150**
    - Pickling Lime (CaOH)

Brulosophy #9 – High Mash pH

- Knockout pH
  - A: 5.15 pH
  - B: 5.7 pH
- OG, FG
  - A: 1.059, 1.013
  - B: 1.059, 1.012
- Beer pH
  - A: 4.55 pH
  - B: 4.65 pH

- Only 8/20 picked the odd beer. P = 0.34
  - Difference not demonstrated.
- Schott: "…I threw in the towel, not going to pretend I could tell the difference…"

Brulosophy #10 - Sodium

- Water
  - A: 118 Ca, 0 Mg, 97 SO4, 140 Cl, 8 Na, RA ~ -85
  - B: 41 Ca, 0 Mg, 97 SO4, 140 Cl, 100 Na, RA ~ -30
- Mash pH
  - A: 5.34
  - B: 5.36
- OG/FG was 1.051/1.012 for both beers.

Brulosophy #10 – Sodium

- Triangle Test, Demonstrated: P = 0.013
  - 16/29 could differentiate the beers
  - 2/16 had no preference
  - 7/16 preferred the Low Sodium
  - 7/16 preferred the High Sodium
  - Huolihan: 5/5 picking odd beer. "High sodium had a cleaner, more pronounced hop aroma with sharper flavors and crisper mouthfeel than the low sodium."

Brulosophy #11 – RO Only

- Czech Pilsner style, 1.057 OG, 34 IBU
  - Water A: Reverse Osmosis only, RA = 0
  - Water B: 50 Ca, 5 Mg, 60 SO4, 60 Cl, RA = -40
  - Both mashes adjusted to pH 5.4 with lactic acid
- OG/FG
  - A: 1.055/1.014
  - B: 1.057/1.015

Brulosophy #11 – RO Only

- Triangle Test, Demonstrated: P = 0.003
  - 14/22 could differentiate the beers
  - 3/14 had no preference
  - 3/14 preferred the straight RO
  - 7/14 preferred the Adjusted RO
  - Del Fiacco: 4/5 picking odd beer. "…more full flavor with a more expressive hop character and aroma."

Brulosophy #12 – Acid vs Acid Malt

- Munich Helles: 1.046 OG, 22.5 IBU
- Water: 62 Ca, 0 Mg, 60 SO4, 68 Cl, RA ~ -40
- Beer A: 7 oz of Acidulated Malt
- Beer B: 7 oz of Pilsner Malt + 19ml of 10% Phosphoric Acid
- Mash pH were essentially the same at 5.4

Brulosophy #12 – Acid vs Acid Malt

- Triangle Test, Demonstrated: P = 0.002
  - 15/23 could differentiate the beers
  - 3/15 had no preference
  - 8/14 preferred the Phosphoric Acid Beer
  - 3/14 preferred the Acidulated malt Beer
  - Huolihan: 4/5 picking odd beer. "…perception of a slightly tart sensation in the back of my throat with the acidulated malt. I preferred the phosphoric acid beer."

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Brulosophy #13 – NEIPA RO or Salts

- NEIPA: 1.056 OG, 53 IBU
- Water:
  - A: RO
  - B: Salts: 111 Ca, 5 Mg, 100 SO4, 150 Cl, RA = -80
    - Plus unspecified amount of lactic acid.
- Mash pH
  - A: 5.4
  - B: 5.2
- FG
  - A: 1.007
  - B: 1.010

Brulosophy #13 - NEIPA RO or Salts

- Triangle Test, Not Demonstrated: P = 0.83
  - 4/16 could differentiate the beers
  - Mendes: 3/4 picking odd beer. "…had to go back and forth multiple times… I perceived the untreated water beer as brighter and more aromatic with a slight alcohol flavor and a touch more bitterness…treated water beer came across as rounder, smoother on the palate, and overall easier to drink."

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Brulosophy Exbeeriment Results

- Demonstrated a Difference
  - #1 – Pilsner: Adjusted vs. (low mineral)
  - #2 – Stout: 167:67 SO4:Cl vs. 55:123
  - #3 – Belgian Pale: 2:1 SO4:Cl vs. 1:1 (Post Ferm!)
  - #6 – IPA: Sulfate to Chloride 150:50 vs. 50: 150
  - #10 – Cal Common: 100 Sodium vs. 8 Sodium
  - #11 – German Pils: Minimum Adjusted vs. RO
  - #12 – Munich Helles: Phosphoric vs. Acidulated Malt

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Brulosophy Experiment Results

- Difference Not Demonstrated
  - #4 – Kolsch: Phosphoric vs. Lactic Acid
  - #5 – IPA: Boil pH, 5.4 vs. 5.1
  - #7 – Oat Pils: Low Mash pH 4.4 vs. 5.3
  - #8 – Bitter: Sulfate to Chloride, 200:100 vs 50:25
  - #9 – IPA: High Mash pH, 5.2 vs 6.4
  - #13 – NEIPA: Adjusted vs. RO

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Questions?

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