Kraft Pulping

Kraft Cycle

Wood Chips

White Liquor, NaS, NaOH

Blowtank

Pulp Washer 37 - 39%

Disintegrator
diss. 44%

Thickener

Green Liquor Storage

Clarifier

Lime

Mud Washer

Limestone NaCO₃

Ca Cycle

Recovery Furnace:
Na₂SO₄ + 2C + heat → Na₂S

Caustizing:
Na₂CO₃ + Ca(OH)₂ → 2NaOH + CaCO₃

Calcining:
CaCO₃ + heat → CaO + CO₂

Slaking:
CaO + H₂O → Ca(OH)₂ + heat

Na Cycle

Weak Wash Storage

WBL = Weak Black Liquor

SBL = Strong Black Liquor

% = Black Liquor Solids

Degrade Tank

Weak Wash Storage

N₂O₃

Kraft Pulping

Kraft Cycle
Standard terms

Total chemical: All Na salts
Active alkali: NaOH + Na₂S
Effective alkali: NaOH + 1/2 Na₂S
Sulphidity: Na₂S/(NaOH + Na₂S)
Total alkali: NaOH + Na₂S + Na₂CO₃ + Na₂SO₄
Total titratable alkali: NaOH + Na₂S + Na₂CO₃

(Usually expressed in equivalents of Na₂O)
  in North America as lb/ft³ or g/L as Na₂O
  International as g/L as Na₂O or NaOH

Chemical composition for bleachable pulp grades

<table>
<thead>
<tr>
<th></th>
<th>White Liquor (g/L as Na₂O)</th>
<th>Black Liquor (g/L as Na₂O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaOH</td>
<td>65 – 75</td>
<td>10 – 15</td>
</tr>
<tr>
<td>Na₂S</td>
<td>25 – 35</td>
<td>6 – 10</td>
</tr>
<tr>
<td>Na₂CO₃</td>
<td>10 – 15</td>
<td></td>
</tr>
<tr>
<td>Na₂SO₄</td>
<td>&lt;2</td>
<td></td>
</tr>
<tr>
<td>Active Alkali</td>
<td>~100</td>
<td>13 – 20</td>
</tr>
<tr>
<td>Effective Alkali</td>
<td>~85</td>
<td>11 - 17</td>
</tr>
</tbody>
</table>
Kraft Chemical Charges

<table>
<thead>
<tr>
<th>Pulp Grade</th>
<th>Active Alkali (% on od wood)</th>
<th>Sulfidity (%)</th>
<th>Liquor/Wood (vol/wt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW Bleachable</td>
<td>16 – 18</td>
<td>30</td>
<td>4:1</td>
</tr>
<tr>
<td>HW Bleachable</td>
<td>14 – 16</td>
<td>25</td>
<td>3:1</td>
</tr>
<tr>
<td>SW Liner</td>
<td>12 – 13</td>
<td>25</td>
<td>4:1</td>
</tr>
</tbody>
</table>

Hydrolysis of sodium sulfide

\[
\text{Na}_2\text{S} + \text{H}_2\text{O} \rightleftharpoons \text{NaOH} + \text{NaHS}
\]

\[
\text{NaHS} + \text{H}_2\text{O} \rightleftharpoons \text{NaOH} + \text{H}_2\text{S}
\]

(The second reaction is not significant at the pH levels of kraft liquors)
Sequence of Events in kraft pulping

- Provide a pathway for liquor penetration into the wood matrix
- Diffusion of HS⁻ and OH⁻ ions throughout the fibre matrix
- Reactions with the wood components
- Diffusion of reaction products to the chip surface
- Dispersion of reaction products in the black liquor

Diffusion of white liquor ions into wood matrix
Major reactions in kraft puling

Delignification occurs in three phases
Carbohydrate reactions

- Alkaline swelling of the fibre wall
- Alkaline dissolution of carbohydrates
- Precipitation of dissolved carbohydrates onto fibres
- Alkaline hydrolysis of acetyl groups
- Alkaline “peeling” of cellulose
- Stopping reactions
- Alkaline hydrolysis of β-glycosidic bonds

Polysaccharide degradation reactions (purified cellulose in NaOH solution)

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$E_{a, \text{Kin}}$</th>
<th>Reaction mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peeling</td>
<td>~100</td>
<td>$\text{Peeling} \rightarrow \text{Cellulose}$</td>
</tr>
<tr>
<td>Stabilization</td>
<td>~134</td>
<td>$\text{Stabilization} \rightarrow \text{Cellulose}$</td>
</tr>
<tr>
<td>Hydrolysis</td>
<td>~150</td>
<td>$\text{Hydrolysis} \rightarrow \text{Cellulose}$</td>
</tr>
</tbody>
</table>

---

Reaction Kinetics

$$- \frac{dL}{dt} = k [L]^a [OH^-]^b [HS^-]^c$$

- $L$ = lignin content (% on o.d. wood)
- $a, b, c$ = reaction order constants
- $t$ = time (hours)
- $k$ = reaction constant $f(T, \text{wood species}, \text{etc.})$
Relative rate of reaction

\[ k = Ae^{-\frac{E_a}{RT}} \]

- \( k \) = rate constant
- \( A \) = pre exponential factor
- \( E_a \) = activation energy
- \( R \) = ideal gas constant
- \( T \) = temperature (°K)

rel. rate = \( \frac{k}{k_{373}} = \exp\left(-\frac{E_a}{R}\left(\frac{1}{T} - \frac{1}{373}\right)\right) \)

Pulping kinetics

- H-Factor

\[ H = \int_0^t \frac{k}{k_{373}} \, dt \]

for \( E_a = 32 \text{ kcal/mole} \)
\( R = 1.986 \text{ cal/(mole K)} \)

\[ H = \int_0^t \left(e^{\frac{432.20 - 16113}{T(t)}}\right) \, dt \]

- Delignification rate

\[ -\frac{dL}{dt} = k[L][OH^-][HS^-] \]

for \([OH\cdot]\) and \([HS\cdot]\) constant during bulk delignification

\[ \ln\frac{L_2}{L} = k_{373}[OH^-][HS^-] \int_0^t \frac{k(t)}{k_{373}} \, dt = K \cdot H \]

where \( K \) = constant
H-Factor Calculation

\[ H = \int_0^T \left( e^{-\frac{43.20}{T(t)}} \right) dt \]

Variables in kraft pulping

<table>
<thead>
<tr>
<th>Process Variables</th>
<th>Wood Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkali applied</td>
<td>Species</td>
</tr>
<tr>
<td>Cooking temperature</td>
<td>Tree component</td>
</tr>
<tr>
<td>Time-to-temperature</td>
<td>Quality</td>
</tr>
<tr>
<td>Time-at-temperature</td>
<td>Chip quality</td>
</tr>
<tr>
<td>Liquor-to-wood ratio</td>
<td></td>
</tr>
<tr>
<td>Liquor sulfidity</td>
<td></td>
</tr>
</tbody>
</table>
Effect of Alkali

Pulp yield = A - B(\log_{10} H)(EA)^n
(n = 0.4 for softwoods)

For six softwoods:
Range: 0.07 - 0.15%
Mean: 0.09%

For five hardwoods:
Range: 0.25 - 0.60%
Mean: 0.41%

Effect of sulfidity

Birch (kappa 25)

Pine (kappa 55)
Effect of temperature

Effect of temperature on yield

Effect of species on yield

<table>
<thead>
<tr>
<th>CHEMICAL COMPOSITION, %</th>
<th>PULP YIELD, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose</td>
<td>Hemicellulose</td>
</tr>
<tr>
<td>White Spruce</td>
<td>44</td>
</tr>
<tr>
<td>Jack Pine</td>
<td>41</td>
</tr>
<tr>
<td>Balsam Fir</td>
<td>44</td>
</tr>
<tr>
<td>White Birch</td>
<td>41</td>
</tr>
<tr>
<td>Maple</td>
<td>41</td>
</tr>
<tr>
<td>Aspen</td>
<td>53</td>
</tr>
</tbody>
</table>
Batch Pulping

Direct

Indirect

Steam

Continuous kraft pulping

Two-Vessel Hydraulic Digester
Continuous kraft pulping equipment

Temperature profile through continuous pulping process
Pulp Washing

• Washing removes ‘black liquor’ from pulp
• Black liquor goes to recovery
• Pulp goes to screening and bleaching

Recovery
Purposes of Chemical Recovery

- Regeneration of alkali: it regenerates the sodium hydroxide consumed in the cook
- Chemical conversion: it converts all sulphur compounds in black liquor into Na$_2$S
- Elimination of pollution: destruction of organic matter dissolved in liquor during pulping stage
- Heat generation: nearly all the heat requirements for the pulping operation are produced
Main Chemical Reactions in Recovery Process

1. Reduction in recovery furnace
   \[ Na_2SO_4 + 2C \rightarrow Na_2S + 2CO_2 \]

2. Causticizing
   \[ Na_2CO_3 + CaO + H_2O \rightarrow 2NaOH + CaCO_3 \]

3. Calcining
   \[ CaCO_3 \rightarrow CaO + CO_2 \]

Black Liquor Properties Which Have Strong Effects on Recovery

1. Concentration of black liquor
2. Liquor viscosity \(\rightarrow\) sprayability, evaporation capacity
3. Organic-inorganic ratio of black liquor solids
4. Heating value of liquor \(\rightarrow\) composition of organics, O/I ratio, liquor oxidation, dead load of inorganics, soap content
Heat Transfer in Evaporators

Evaporators are heat transfer devices with a heat supply and heat sink

– Heat supply: latent heat of steam and condensate flash

– Heat usage: sensible heat (to bring liquor to boiling) & latent heat (to evaporate water)

Steam economy ~ evaporation efficiency = kg of water evaporated per kg of steam used (4.5 - 6.0 kg/kg in the multiple effect evaporators)

Several different types of evaporator technologies can / have been used.
Multiple Effect Evaporators

- Steam is fed to only one evaporator body
- The steam condensate, and vapour from liquor evaporation in that body, are “flashed” to a second evaporator operating at lower pressure
- Water evaporated in effect n is used for heating effect n+1
- Liquor and steam flow are counter-current
- The multiple effect principle results in very high steam economy and low evaporation costs

http://en.wikipedia.org/wiki/Multiple-effect_evaporator

Disadvantages

- Heat transferred in each effect is roughly equal. If U in effect # 1 drops by 50 % (due to scaling), the evaporation capacity of a six effect system is reduced by 17 %
- Foaming and liquor entrainment in the vapour stream lead to steam side fouling and corrosion
- Stripping of sulphur gases from the liquor can result in non-condensable gas blanketing, which effectively reduces the area available for heat transfer
Black Liquor Oxidation

- Essential for odor reduction prior to recovery furnace
- Two types of systems:
  - Weak black liquor (15-20% solids)
  - Strong black liquor (40-50 solids)
- Foam from the soaps/fats from the tree is a major problem. Need de-foaming systems
- Purpose to oxidize residual Na2S to Sodium Thiosulfate
- First stage can be on WBL or SBL. Second stage should be before direct contact evaporators.

\[
2Na_2S + 2O_2 + H_2O \rightarrow Na_2S_2O_3 + 2NaOH \]

sodium thiosulphate

\[
4CH_3SH + O_2 \rightarrow 2(CH_3)_2S_2 + 2H_2O \]

methyl mercaptan dimethyl disulphide

Both Na2S and CH3SH are the largest contributors to TRS (Total Reduced Sulphur) emission non-compliance
Recovery Boiler

- The recovery boiler process has several unit processes:
  - Combustion of organic material in black liquor to generate steam
    - Send to turbine for energy production
  - Reduction of inorganic sulfur compounds to sodium sulfide, which exits at the bottom as smelt
  - Production of molten inorganic flow of mainly sodium carbonate and sodium sulfide, which is later recycled to the digester after being re-dissolved
  - Recovery of inorganic dust from flue gas to save chemicals (sulphor and sodium)
  - Production of sodium fume to capture combustion residue of released sulfur compounds


CMPC Celulosa Santa Fe Recovery boiler is one of the newest boilers in South America

Howe Sound Pulp and Paper Recovery boiler
Corrosion in Recovery Furnace

- Floor tube cracking and hydroxide attack around air ports are problems in boilers with composite tubes.
- Reactions between H₂S and CH₃SH and iron in carbon steel can cause rapid corrosion of water wall tubes.
- Corrosion close to the surface of the mud drum is problematic in boilers with two drums.
- Acidic corrosion, below the dew point of gases, can reduce the electrostatic precipitator efficiency and lifetime.
Objectives of Recausticizing

- Regenerate NaOH
- Produce enough white liquor for cooking (and other needs)
- Produce a high quality liquor at minimal cost

Definitions

\[
\text{Causticity} = \frac{\text{NaOH}}{\text{NaOH} + \text{Na}_2\text{CO}_3} \times 100
\]

\[
\text{Causticizing efficiency} = \frac{\text{NaOH}_{wl} - \text{NaOH}_{gl}}{(\text{NaOH}_{wl} - \text{NaOH}_{gl}) + \text{Na}_2\text{CO}_3} \times 100
\]

Total titratable alkali = TTA = NaOH + Na₂S + Na₂CO₃
Recausticization Reactions

\[
CaCO_3 \xrightarrow{\text{heat}} CaO + CO_2
\]

\[
CaO + H_2O \rightarrow Ca(OH)_2
\]

\[
Ca(OH)_2 + Na_2CO_3 \rightarrow 2NaOH + CaCO_3
\]
Lime Kiln

Overview of Kraft liquor cycle

Smook 1992
Chemical Pulp Bleaching I
Overview

• Objectives and goals
• Bleaching chemistries used
  – Reactions with lignin and cellulose
  – Typical bleaching conditions
  – Bleaching kinetics
• The bleaching stage
• Delignification partial sequences
• Brightening partial sequences

Why Pulps can be Bleached

• Cellulose is almost colourless
• Lignin - can be removed or modified to absorb less light
Objectives of Pulp Bleaching

“To produce a strong, bright and clean pulp in an environmentally friendly manner at minimum cost.”
Objectives of Pulp Bleaching

- Removal of the majority of lignin in the delignification stages: attain target kappa number
- Obtain target brightness levels in the brightening stages
- Preserve carbohydrates to maintain pulp yield and strength
- Treat the pulp uniformly
- Minimize all costs

What Happens During Bleaching?

- Pulp is made whiter and brighter
- Lignin, resins, metal ions, etc. are removed
- Pulp and fibre properties are altered (*e.g.* viscosity)
- Pulp is made suitable for its end use
Factors Affecting the Choice of the Bleaching Process Used

- Pulping process (kraft, soda or sulfite)
- Wood species
- End use of pulp
- Minimum colour reversion
- Environmental constraints
- Cost

Delignification and Brightening

- Pulp bleaching is accomplished in two stages: delignification and brightening
- Delignification removes the residual lignin (3 - 7%) that remains after cooking.
- Brightening is accomplished in a series of oxidation stages (one to four)
- Brightness ceiling typically 90%+ ISO
Control Targets in Bleaching

Lignin Content
Kappa Number
% lignin = 0.15 \times \text{kappa}

Brightness
ISO Brightness
457nm light reflected from sheet under controlled conditions

Bleaching Chemicals

<table>
<thead>
<tr>
<th>Stage</th>
<th>Chemical Name</th>
<th>Symbol</th>
</tr>
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<tbody>
<tr>
<td>C</td>
<td>Chlorine</td>
<td>Cl₂</td>
</tr>
<tr>
<td>D</td>
<td>Chlorine Dioxide</td>
<td>ClO₂</td>
</tr>
<tr>
<td>E</td>
<td>Sodium Hydroxide</td>
<td>NaOH</td>
</tr>
<tr>
<td>H</td>
<td>Sodium Hypochlorite</td>
<td>NaOCl</td>
</tr>
<tr>
<td>P</td>
<td>Hydrogen Peroxide</td>
<td>H₂O₂</td>
</tr>
<tr>
<td>O</td>
<td>Oxygen</td>
<td>O₂</td>
</tr>
<tr>
<td>Z</td>
<td>Ozone</td>
<td>O₃</td>
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</tbody>
</table>
Bleaching Variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Expressed as:</th>
<th>Effect</th>
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</thead>
<tbody>
<tr>
<td>Chemical</td>
<td></td>
<td>• chemical reactions</td>
</tr>
<tr>
<td>Pulp consistency</td>
<td>$C_m = \frac{\text{mass of fibre}}{\text{total suspension mass}}$</td>
<td>• chemical concentration</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• reaction rate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• suspension rheology</td>
</tr>
<tr>
<td>Charge</td>
<td>wt/wt, %</td>
<td>• treatment</td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>• extent of reaction</td>
</tr>
<tr>
<td>Time</td>
<td>s/min/hr</td>
<td>• reaction rate</td>
</tr>
<tr>
<td>pH</td>
<td>pH</td>
<td>• duration of reaction</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Brightness</th>
<th></th>
<th>Delignification and brightness development</th>
</tr>
</thead>
<tbody>
<tr>
<td>28% lignin</td>
<td></td>
<td>C</td>
</tr>
<tr>
<td>1% lignin</td>
<td></td>
<td>E</td>
</tr>
<tr>
<td>5% lignin</td>
<td></td>
<td>D</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D</td>
</tr>
</tbody>
</table>

Delignification Brightening
Rate of Lignin Removal in the Initial Stages of Kraft Pulp Chlorination

![Graph showing rate of lignin removal in Kraft pulp chlorination](image)

- **Lignin, % on Pulp**
- **Time, s**

![Graph showing kappa number over time](image)

- **Kappa Number**
- **Time, min.**
Ozone Delignification

- Ozone is a powerful oxidizing agent which reacts readily with most organic materials.
- First patent describing the use of ozone in bleaching of fibres for papermaking issued in 1889.
- Commercial implementation delayed due to technical issues (mixing, ozone generation), higher pulp production costs, and poorer pulp quality (lower strength, lower brightness).
- 13 installations by 1995.
- Future D/Z?
Ozone Delignification

Kappa Number after Z-stage vs. Ozone Charge, % on O.D. Pulp

- **Kraft pulp**
  - Initial kappa: 22.4
  - After O: 15.8
  - After O: 11.7

Ozone Delignification

Viscosity after Z-Stage mPas vs. Ozone Charge, % on O.D. Pulp

- **Kraft pulp**
  - Initial kappa: 22.4
  - After O: 15.8
  - After O: 11.7
Chemical Pulp Bleaching II
Overview

• Bleaching sequences
• D(EOP)D(EP)D sequence
• Bleaching equipment
  – washers
  – mixers
  – residence towers
• Challenges met in the 90’s
• Challenges for the future - 2000 and beyond

The Bleaching Stage

Mixer → Mixer → Reactor → Washer

Steam, Chemical, Water

Washed pulp from previous stage

Effluent

Washed pulp to next stage
Asymptotic Bleaching Levels

Bleaching Sequences

- Delignification Partial Sequences
  - CE
  - C₀E
  - (DC)E
  - C(EO)
  - O(CE)
  - ODE
  - OD(EO)

- Brightening Partial Sequences
  - H
  - D
  - HD
  - HDED
  - DED
  - D(EP)D
Bleaching Sequences

1970’s
- CEH
- CEHH
- CEDED
- $C_0EDED (5-10\% D)$
- $(C_{30}D_{70})(E+O)DED$
- $O(D_{70},C_{25}D_{5})(E+O)D$

1990’s
- OD(EOP)D(EP)D
- OZEP

Future
- ?

The D(EOP)D(EP)D Sequence
Typical Bleaching Conditions
OD(EOP)D(EP)D

<table>
<thead>
<tr>
<th>Chemical Applied, kg/t</th>
<th>O</th>
<th>D</th>
<th>EOP</th>
<th>D</th>
<th>EP</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>O2</td>
<td>25</td>
<td>-</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ClO2</td>
<td>-</td>
<td>20</td>
<td>-</td>
<td>8</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>NaOH</td>
<td>25</td>
<td>-</td>
<td>25</td>
<td>5</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>H2O2</td>
<td>-</td>
<td>-</td>
<td>3</td>
<td>-</td>
<td>~3</td>
<td>-</td>
</tr>
<tr>
<td>Temperature, °C</td>
<td>95</td>
<td>50</td>
<td>70</td>
<td>70</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Residence time, min</td>
<td>60</td>
<td>30</td>
<td>60</td>
<td>180</td>
<td>60</td>
<td>180</td>
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<tr>
<td>Residual Oxidant</td>
<td>yes</td>
<td>nil</td>
<td>-</td>
<td>tr</td>
<td>-</td>
<td>nil</td>
</tr>
<tr>
<td>Consistency, %</td>
<td>12</td>
<td>3</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
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<tr>
<td>End pH</td>
<td>11+</td>
<td>2.5</td>
<td>10.5</td>
<td>3.5</td>
<td>10.5</td>
<td>4</td>
</tr>
<tr>
<td>kappa target</td>
<td>15</td>
<td>-</td>
<td>~3</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Brightness target (ISO)</td>
<td>-</td>
<td>-</td>
<td>83</td>
<td>-</td>
<td>90</td>
<td>-</td>
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</tbody>
</table>

Diagram:
- Washer
- Pulp from previous stage
- Pump
- Chemical(s)
- Mixer
- Steam
- Tower
- Pulp to next stage
- Washer
Bleaching Equipment

- Pumps
- Mixers
- Reactors (Residence Towers)
- Washers
- Sensors

Medium-Consistency Pulp Mixer
MC Mixer Installation

Bleach Towers
Typical Tower Design

<table>
<thead>
<tr>
<th>Stage</th>
<th>Consistency (%)</th>
<th>Residence Time (h)</th>
<th>Tower Configuration</th>
<th>Tower Aspect Ratio (H/D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>10 - 12</td>
<td>0.75 - 1.0</td>
<td>UF</td>
<td>7 - 10</td>
</tr>
<tr>
<td></td>
<td>20 - 32</td>
<td>0.5</td>
<td>DF</td>
<td>3 - 4</td>
</tr>
<tr>
<td>C, (CD), D 100</td>
<td>3 - 4</td>
<td>0.5 - 1.0</td>
<td>UF</td>
<td>4 - 7</td>
</tr>
<tr>
<td></td>
<td>10 - 12</td>
<td>0.5</td>
<td>UF</td>
<td>4 - 7</td>
</tr>
<tr>
<td>Z</td>
<td>10 - 12</td>
<td>0.05 - 0.08</td>
<td>UF</td>
<td>10 - 12</td>
</tr>
<tr>
<td>Eo, Eop (tube)</td>
<td>10 - 12</td>
<td>0.05 - 0.5</td>
<td>UF+</td>
<td>9.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.0 - 2.0</td>
<td>DF</td>
<td>4 - 5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-2.0</td>
<td>UF</td>
<td>4 - 5</td>
</tr>
<tr>
<td>H</td>
<td>10 - 12</td>
<td>0.5 - 3.5</td>
<td>DF</td>
<td>4 - 5</td>
</tr>
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<td>D</td>
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<td>0.5</td>
<td>UF+</td>
<td>9</td>
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<td>2.5 - 4.5</td>
<td>DF</td>
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<td>3.0 - 5.0</td>
<td>UF</td>
<td>5</td>
</tr>
</tbody>
</table>

Tower Design - In General

- **Tower Configuration**
- **Low and Medium Consistency (3 - 12%)**
  - Liquid chemicals: upflow or downflow
  - Liquid chemicals with high vapor pressure: upflow (tower or tube)
  - Gaseous chemicals: upflow (tower or tube)
- **High Consistency (20% - 40%)**
  - Downflow
- **Aspect Ratio**
- **Low consistency: 4 - 7**
- **Medium consistency: no gas 4 - 7 gas > 8**
Future Trends in Bleaching

• Greater use of oxygen compounds
• Progressive system closure
• More efficient chemical use
  – carefully chosen kappa targets
  – improved chemical contacting/mixing
  – hexenuronic acid removal
  – new chemical additives