The top ten factors in kraft pulp yield

ABSTRACT

Kraft pulp yield depends on a plethora of factors: the nature of the wood and the quality of the chips, the cooking recipe (especially the key independent variables – alkali charge, sulphidity, temperature, and kappa target), the pulping equipment, and so on. Here, the factors have been assembled into a "top ten" list, and are assessed in terms of relative importance, potential to influence yield values, and contribution to practical knowledge of how pulp yields can be improved. The ten factors can be re-ordered at will, to rank the magnitude of the yield changes they can produce, for example, or to see which factors have the highest potential for yield improvement at modest cost.

WHAT ARE the principal factors affecting pulp yields in kraft mills? How comprehensive is our understanding of them? Are there practical ways to use existing knowledge to improve yields?

To address these questions, here is a Top Ten list (Fig. 1) of the key factors to consider, followed by brief descriptions of why each is important, what the size of the yield gain might be, and how substantial and reliable the information base is. The focus is on practical opportunities for yield gains in kraft mill operations, tying them to scientific knowledge of cause-and-effect relationships. The broad perspective is two-fold: how wood and chemistry interact in the kraft pulping process, and why uniformity of treatment (whether chemical or mechanical) matters. An anthology of papers on the subject of kraft pulp yield is also available /1/.

The ten factors have been assembled in the same order as fibrelines, i.e., from chips through pulping to bleaching. The order can be changed for different purposes, as will be obvious later when they are ranked for magnitude of potential yield gain and also for what is practical to do at modest cost.

Wood species

Wood, an organic raw material, consists of polysaccharides (cellulose and hemicelluloses), lignin, and extractives. Their concentrations vary substantially among commercial wood species /2,3/: cellulose, approximately 40–50% of wood; hemicelluloses, 25–35%; lignin, 15–30%; extractives, 2–10%. The higher the polysaccharide content (especially cellulose) and the lower the amounts of lignin and extractives, the higher will be the yield of pulp from wood. Aspen is a leading example – with lignin content often below 20% and (acetone) extractives below 3%, it cooks rapidly to the highest bleachable-grade kraft pulp yield in industrial practice, typically about 55% at kappa 12. Western red cedar, with an unusually high extractives content, is at the low end of the spectrum, providing a bleachable-grade pulp yield in the low 40s at kappa 30 /4/.

In commercial kraft pulping practice worldwide, the typical yield range (unbleached pulp, in percent from wood) is about mid-40s to mid-50s for bleachable-grade hardwood pulps, and about 40–50 with softwoods (Fig. 2). We can widen the softwood range to about 60% by including linerboard basestock, the high-kappa end of the kraft pulping spectrum. It is also possible to extend the lower limits of these ranges by invoking the use of sawdust or fines (or decayed wood of any particle size).

Surprisingly for a worldwide industry which has been in business for many decades, there is no simple, fast, and cheap way to determine the gross chemical composition of the wood in use.

The chemical composition of wood is probably the primary variable in kraft pulp yield. Fig. 3 shows normal yields in conventional research-scale kraft pulping of species-pure chips to bleachable-grade kappa numbers versus their typical lignin contents in the wood. This relationship makes reasonable sense: the higher the lignin content – which will be mostly removed in pulping – the lower the pulp yield. It is remarkably accurate over a yield range of 42–55%: Pulp yield = -0.69[Lignin] + 65.8 (r² = 0.95). North American wood species are illustrated in Fig. 3, but major commercial species elsewhere in the world will conform to this general picture.
Wood anatomy
The physical nature of wood also plays an important role in yield. Large differences exist among wood species, especially in percentage of “fibres” (the preferred cell type for papermaking) versus that of less desirable cells (e.g., ray parenchyma in softwoods, vessel elements in hardwoods) /5/. This is compounded by large ranges in the principal wood fibre dimensions: length, diameter, and cell wall thickness /6/. For example, loblolly pine kraft pulp fibres can be five times longer than sugar maple fibres. Further, there are dimensional differences between earlywood and latewood, and between juvenile and mature wood. Of all of these, only fibre length distribution is routinely measured in the kraft pulping world.

From a papermaker’s perspective, a more appropriate concept might be the yield of papermaking fibres from wood. In this sense, different wood species offer very different potential yields. If only long, narrow fibres are sought, for example, then softwoods have a large advantage over hardwoods, in which wood anatomy is much more diverse (Fig. 4). But by acknowledging that hardwoods inevitably contain significant amounts of vessel elements, we can add them back since they are part of the pulp yield, bringing the hardwood cases much closer to the softwood ones. Still, there is a substantial amount of cell material in all woods that is not ideal from a papermaking standpoint.

We can generalize with the following observations:
• The greater the range of wood cell types, the wider will be the dimensional ranges of length, width, and cell wall thickness in the raw material before pulping, and hence in the kraft pulp which is produced.
• The anatomy of hardwoods is much more complex and – in some papermaking ways – adverse than that of softwoods.

Chip size distribution
In chip size, two things are clear – thickness is the principal dimension of concern in kraft pulping, and 2–8 mm thick chips are ideal /7/. Thickness distributions are routinely measured in chip classifiers, and modern chip thickness screening systems in mills are capable of controlling the thickness range reasonably well. Sadly, they often don’t. Greater precision in chip making would help, whether during sawmilling operations or in log chipping. Undersized “chips”, although they pulp rapidly, carry a substantial yield penalty. With oversized chips, the danger is in generating rejects, inherently a penalty in mills producing bleachable-grade pulp whether the rejects are re-processed or are removed from the fibreline. If small wood particles can go to a dedicated, separate production line, and overthick chips are processed mechanically to make them more amenable to pulping, significant yield gains can be obtained when pulping only the properly-sized chips, on the order of 1–2%.

Fig. 5 illustrates two thickness distributions of same-species softwood chips on final delivery to two kraft digesters. The mill on the left achieves excellent control from a chip thickness screening plant with disc screens and slicers. From pilot-plant pulping, these chips gave 46% pulp yield at 25 kappa when only the 2–8 mm fraction (containing 95% of the total mass) was cooked. Using mass fractions and reasonable assumptions to calculate the fractional yields shown in Fig. 5, the actual total yield from this chip furnish was 45.8%.

The older mill on the right had rudimentary chip screening and therefore a much broader thickness distribution. At 25 kappa, the penalties with the undersized and oversize fractions were more serious, bringing the total yield down to 45.1%.

Note that with significantly less 2–8 mm material present, its fractional yield was ten percentage points lower.

A yield difference of 0.7% may seem rather small, but at a pulp production rate of 1000 tpd the older mill requires 12,000 t more wood (on an oven-dry basis) annually. That can easily translate into a cost increase of a million dollars or more a year. The penalty will be worse when accounting for wasted volume in the digester occupied by overthick chips, higher alkali consumption, greater knotter rejects recycling costs, more shives going forward, less uniform pulp, and higher bleaching costs.

A chip thickness screening plant is a necessary part of a modern kraft pulp mill. But simply buying and installing such a plant is not enough – it must also be maintained, tested periodically, adjusted, and improved.

Chip quality (other than chip size)
Many yield-related considerations fall into this category. In mixed-species chip furnish, the proportions of the species, each with its own yield potential, will affect overall pulp yield. Moisture content can influence yield values if green wood (rather than dry wood) is the basis for calculation; it can also affect the efficiency of pulping if the “recipe” changes (e.g., an unintentional change in alkali charge due to an unseen change in wood moisture might penalize pulp yield). Mechanical damage to wood fibres can make them more susceptible to chemical attack during pulping, lowering yield. Biological decay, bark, or the presence of biological knots and overthick chips in chip furnish all impair pulp yield relative to fresh, sound wood of suitable thickness.

Any of these factors may represent only a small yield penalty; together, they may reduce pulp yield by 2–4%.
not a practical thing to do, but decreasing the over-thick fraction substantially would help. Since the trial, chip thickness screening and overthick chip crushing have been installed on the hardwood side at Espanola.

- **Pilot-Plant Pulping**: Due to good chip pre-steaming practice, ideal temperature control, and homogeneity of impregnation and cooking in small research digesters, greater uniformity of pulping resulted in a significant yield advantage (1.5%) regardless of whether reference chips or mill chips were cooked.

- **Wood Species**: Species analysis of basket pulps from mill “birch” chips showed that they actually contained 24% maple on average. Taking maple as one-quarter of the mass, and assigning this fraction a 2% yield penalty from wood relative to white birch /4/, a 0.5% yield deficit was calculated.

Overall, the four factors illustrated here added up to a potential yield gain of 5.5%, whether associated with the Kraft baseline yield or with the PS-AQ yield. Achieving best performance in all of these factors significantly improves pulp yield.

**Conventional pulping chemistry**

Among the primary independent variables of kraft pulping, high alkaline charge, low sulfidity, high maximum temperature, and high lignin content in the wood are the most dangerous for inferior yield, potentially reducing the value by several percentage points. By contrast, the higher the cellulose-to-hemicellulose ratio in the wood, the better. Lower extractives content is also desirable. Liquor-to-wood ratio can affect yield in that it has a strong influence on pulping rate, and therefore the time during which the polysaccharides (especially hemicelluloses) are degraded by alkaline attack. Hardwood lignin is chemically different from softwood lignin, and accounts for part of the reason why hardwoods often have higher pulp yields (and faster delignification rates).

How the main independent variables of kraft pulping affect kraft pulp yield is clearly explained in Kleppe’s classic paper “Kraft Pulping” /9/. Higher alkaline charge decreases pulp yield at a given kappa number, all other factors held constant, both with softwoods and hardwoods (Fig. 7). For every 1% increase in effective alkaline charge (NaOH basis) with softwoods, there is a 0.15% penalty in yield. The problem is three times worse with hardwoods, due mainly to the higher proportion of hemicelluloses (especially xylans) and their susceptibility to alkaline attack.

An independent example with Kraft pulping of aspen to 15 kappa showed these results: total yield of 55.6% at 11% effective alkaline, 54.4% yield at 13.5% EA, and 52.8% yield at 17% EA. Thus, an increase of 6% effective alkaline led to a yield loss of 2.7%, just as predicted (i.e., 6 x 0.45%).

Although not particularly important in industrial Kraft pulping (the majority of which is done at or above 30% sulfidity), how sulfidity affects yield is informative. Again from Kleppe /9/, with birch (at a kappa target of 25), the yield plateau at 54% comes at 30% sulfidity. At 0% sulfidity, pulp yield is about 50% instead, a deficit of 4%; note that pulp rate is much slower as well. With Pine at 55 kappa number, the 51% pulp yield plateau is at ~40% sulfidity.

**Effect of Sulfidity on Pulp Yield**

Fig. 8. Sulfidity has a minor effect, providing that it is at the plateau level of 30% or above (this is true for the majority of Kraft mills).

**Effect of Temperature on Pulp Yield**

<table>
<thead>
<tr>
<th>Digester</th>
<th>Total yield, %</th>
<th>Difference in TY, %</th>
<th>Ascribed to chips</th>
<th>Ascribed to EA</th>
<th>Yield Loss due to Tmax, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>45.4</td>
<td>2.1</td>
<td>-0.3</td>
<td>-0.1</td>
<td>1.7</td>
</tr>
<tr>
<td>B</td>
<td>43.3</td>
<td>-</td>
<td></td>
<td></td>
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</table>

**Fig. 9. Maximum temperature of cooking has a major effect on pulp yield — although it speeds up the delignification rate, it accelerates polysaccharides degradation even more.**
ity. At 0% sulphidity, pulp yield is 48%, a deficit of 3%. Again, the pulping rate decreases significantly with lower sulphidity.

In both cases, then, pulp yield is directly related to sulphidity, but not in a linear manner. Sulphidity needs to be at or above 30% for optimum yield and rate reasons.

The maximum temperature of pulping is also important for yield. In the case shown in Fig. 9, two chip furnishes from the same wood species were being delivered to two continuous digesters. They were pulped in a pilot-plant digester at process conditions taken from the two mill digesters (A: 18.5% effective alkali, 163°C maximum; B: 19.1% EA, 175°C max.). Case A had 86% 2-8 mm chips and 7% > 8 mm chips; Case B, 79% 2-8 mm chips and 14% > 8 mm chips.

The difference in total yield at kappa number 30 was 2.1%. When adjusted for the differences attributable to chip thickness distribution and applied effective alkali, the yield deficit due to the 12°C higher maximum temperature in Digester B was 1.7%.

Modified pulping chemistry

The era of modified kraft pulping (originally called extended delignification) which began in the 1980s was founded on chemical principles intended to make kraft pulping more selective for delignification over polysaccharide degradation. Combined with appropriate changes in mill digesters, some yield benefits have accrued. Liquor displacement batch systems can improve yield over conventional batch systems (as measured by hanging baskets) by 1–2%/10/. Continuous digesters with multiple white liquor inputs and black liquor extractions appear to offer a yield advantage – particularly with hardwoods – of up to 4%/11/. In general, however, evidence for a universal yield benefit with modified kraft pulping equipment is scanty.

Modifying kraft pulping with additives (e.g., anthraquinone, or polysulfide, or both) can improve pulp yields by about 1–3%. The research knowledge is extensive and deep /12/, and both additives have been used for the past 30 years in mills scattered around the world. An obvious advantage with AQ is that it can work in all types of kraft digesters – no equipment changes are required. To achieve maximum benefits with AQ, its strategy of use needs to be based on optimizing all the key factors in kraft delignification, including alkali charge, sulphidity, and kappa target. Fig. 10 shows an example /13/.

A recent implementation of PS-AQ pulping of hardwoods demonstrated that the change from kraft resulted in a yield gain of about 2% whether measured by hanging baskets in the mill or in pilot-plant pulping using the chips and cooking liquors from the mill /8/ (see also Fig. 6).

Occasionally, an astonishing possibility emerges, such as alkali sulphite-AQ pulping /14,15/. Although not in use industrially because of its slow delignification rate and complex chemical recovery issues, AS-AQ pulping can provide yield gains of 5–10% (Fig. 11), depending on the scenario. No other industrially-feasible process chemistry change can do better.

**Mill digester systems**

Digester equipment considerations can have a big influence on yield in kraft pulping. Especially important are the chip pre-steaming and liquor impregnation steps. Advanced batch and continuous digesters do an effective job of chip pre-steaming by providing enough contact time with atmospheric steam (15+ minutes), but most digester systems have either no deliberate pre-steaming or not enough, even when it is a combination of atmospheric and low-pressure regimes. When air removal and water saturation of the inner void spaces in wood chips are inadequate, the result is a less-than-perfect liquid environment for pulping, leading to more heterogeneous delignification and inferior yield.

Good impregnation is always a key to good kraft pulping. It needs to be long enough (usually 30+ minutes) and at a low enough temperature (120° ± 5°C) to ensure that the liquid-phase chemistry is ready to begin everywhere inside the chips when they are taken to delignification temperature. Fig. 12 illustrates results from kraft pilot-plant experiments on two softwood sawdust furnishes from a mill operating M&D digesters /16/. The M&D operations were simulated by combining the sawdust and cooking liquor in bombs and driving the temperature to 185°C as fast as possible (10 minutes). Even when starting with tiny sawdust-sized wood particles, plenty of rejects were generated. But when we used conventional kraft conditions designed for chips, including a 90-minute ramp of 1°C/min to cooking temperature for graceful impregnation, the rejects decreased by about two-thirds, meaning that the screened pulp yield rose by 2%. This case shows that extreme impregnation conditions can carry a significant yield penalty.

Pilot-plant experiments have also shown that if chips are thoroughly pre-steamed and impregnation with white liquor is done with good temperature control, then bulk liquor circulation through the cooking chip column inside a steam-jacketed 20L digester is not vital in producing kraft pulp of high yield and quality. Forced liquor circulation in mill digesters is a means to try to overcome temperature and chemical concentration gradients created during filling and impregnation. It is no surprise that the best liquor displacement batch digesters have the lowest measured kappa variability inside them /10/.

The era of modified kraft pulping has fostered longer and slower delignification in continuous digesters and more effective impregnation in liquor displacement batch digesters. Both provide an inherent advantage in selectivity (although the main benefit seems to be better preservation of cellulose integrity).

Together, all of these factors can improve pulp yields by several percentage points.
The yield gap widens in four yields. For the highest four yields, total yield = 93% of kappa. Raising the kappa target of 20–30% can avoid unnecessary mechanical degradation by process changes. But attention is required to achieve the right selectivity during delignification and ECF bleaching together. Fig. 13 provides a generic softwood case.

For kraft pulping, the slope of a softwood line to -30 kappa is 0.15 ± 0.05; for hardwoods to -15 kappa, the slope is the same. Both are straight lines. With softwoods, the line represents the bulk delignification phase starting from about 100 kappa (the high-yield end of kraft pulping), and is a fact which cannot be changed easily. The kappa case in Figure 13 is for a softwood with a pulp yield of 47% at kappa 30.

With oxygen delignification, the slope is about 0.10, and extends down to perhaps kappa 15 before beginning a steeper fall /18/. With final lignin removal, in theory the slope is about 0.05; this is chemically close to what ECF bleaching actually does. In all three cases, lower slope means better selectivity during lignin removal, the right direction for yield enhancement.

Several aspects of yield/kappa relationships need to be remembered:

- There are non-linear consequences for yield when either pulping or oxygen delignification is taken below its practical kappa limit where the selectivity for lignin removal is lost.
- The yield gap widens in favor of oxygen delignification over pulping as kappa number decreases.
- Raising the kappa target of pulping lifts the whole picture to higher yield, notwithstanding the higher cost of removing residual lignin later in the process line.

**Yield/kappa relationship**

The typical yield/kappa relationship for kraft pulping (as illustrated in Fig. 13) requires some caveats. There is, of course, a yield intercept which is strongly related to wood species, chip size, and pulping conditions. The straight line represents the bulk delignification phase, which covers almost the whole kappa range of commercial kraft pulping from high-kappa linerboard base stock to bleachable-grades.

Fig. 14 amplifies the meaning of a specific yield/kappa relationship. This is a spruce/pine/fir case in which pilot-plant kraft pulping of 2–8 mm thick chips was done at five H-factors (the highest one was duplicated). Because the fibre liberation point with softwoods is at about kappa 40, screened yield equals total yield at all but the highest kappa level. Three linear regressions can be calculated:

- For all six total yield values, total yield = 0.12(kappa) + 41.3 $r^2 = 0.95$
- For the highest four yields, total yield = 0.11(kappa) + 42.0 $r^2 = 0.94$
- For the lowest three yields, total yield = 0.22(kappa) + 38.9 $r^2 = 0.98$

This demonstrates that where you stop kraft pulping has a significant effect on pulp yield. For bleachable grades, the idea is to aim for the end of the bulk delignification phase without falling into the residual phase. Being seduced by ever lower kappa numbers prior to oxygen delignification or bleaching has its price!

With hardwoods, only bleachable-grade pulp is made, and the entire kappa range is about 12–18, so there is much less room for unintentional overpulping. The use of an excessive alkali charge is the greater risk.

At the low-kappa end, the onset of the residual delignification phase will begin to increase the slope rapidly, sacrificing yield
A Short Wish List

Lignin-free trees
Extractives-free trees
Hardwoods with no vessel elements
CTS plants which perform to specifications (and receive regular audits)
Practical working knowledge of kraft pulping chemistry a qualification for digester operators

Fig. 15. Substantial yield improvements would come from all of these items. While the first three remain intractable, the last two are possible today.

Magnitude of Change

<table>
<thead>
<tr>
<th>Wood species</th>
<th>Factors</th>
</tr>
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<tbody>
<tr>
<td>SW to HW</td>
<td>14%</td>
</tr>
<tr>
<td>SW to SW</td>
<td>8%</td>
</tr>
<tr>
<td>HW to HW</td>
<td>7%</td>
</tr>
<tr>
<td>AS-AQ vs. conventional kraft</td>
<td>6%</td>
</tr>
<tr>
<td>SW</td>
<td>6%</td>
</tr>
<tr>
<td>HW</td>
<td>10%</td>
</tr>
<tr>
<td>PS-AQ vs. conventional kraft</td>
<td>3%</td>
</tr>
<tr>
<td>SW</td>
<td>3%</td>
</tr>
<tr>
<td>HW</td>
<td>3%</td>
</tr>
<tr>
<td>Add oxygen delignification</td>
<td>2%</td>
</tr>
<tr>
<td>Improve impregnation and cooking uniformity</td>
<td>2%</td>
</tr>
</tbody>
</table>

Fig. 16. When ranked according to magnitude of potential yield gain, the top ten factors emerge in this order. Very few options offer individual gains above 3%.

despite the further slow decrease in kappa number. Because the residual lignin is more resistant to delignification while the polysaccharides continue to degrade, the selectivity of kraft pulping becomes progressively worse – the slope of the line becomes steeper.

This relationship is a crucial aspect of every kraft pulping scenario, and it should be known for every mill operation. Often, that is not the case. To obtain accurate numbers, such information is determined in research-scale pulping. It should be done routinely when any significant changes are made in chip furnishes and cooking recipes, including any proposed use of pulping additives.

Wish list

Although industrial kraft pulping practice has changed slowly and incrementally over the years, it is always useful to imagine how it could be made better, and by how much. Figure 15 lists some possibilities, from the far-fetched to the practical:

- Lignin-free trees: In Factor 1, Fig. 3, the linear regression suggests that the lignin-free case has a Y-intercept of 66%, far higher than any kraft pulp yield currently obtained commercially.
- Extractives-free trees: The same general argument applies. Because there is no great business in by-products from extractives any more, it would be nice to avoid dealing with extractives at all.
- Hardwoods without vessel elements: The wood would be denser, providing higher pulp yield per unit volume of digester space, and the pulp would be more uniform, allowing improvements in stock refining, papermaking, coating, and printing.
- Chip thickness screening: Most CTS plants don’t come close to their original specifications for segregating and controlling chip dimensions, nor work consistently well in cold-weather locations. Overthick chip processing spans the range from very good to abysmal /17/.
- Working knowledge: Training of digester operators is not as good as it should be (especially in North America). There is usually no certification of personal knowledge of the chemistry of pulping, so digesters tend to be treated foremost as mechanical entities. Is this satisfactory for the operation of chemically complex systems worth upwards of $100 million that produce tens of billions of dollars worth of pulp per year? Standards are much stricter in many other lines of work, including regular continuing education plus re-testing. Why not in our business?

Having assembled this Top Ten list for kraft pulping yield, it is possible to rank the factors in a variety of ways. Fig. 16 does this based on magnitude of yield gain. For example, a bleachable-grade kraft swing mill could gain 14% going from the lowest softwood yield to the highest hardwood one (Figs. 2 and 3). No mill has the wood basket to do this. But in the northern boreal forest zone, a 7–8% yield gain is routine when going from spruces to aspen. The same is true in hardwood mills going from maples to aspen.

Alkaline sulphite-AQ pulping has been done industrially, but only briefly and confined to two mills. In the right circumstances, its use in linerboard production could be interesting from a yield perspective. Unfortunately, slow pulping rate and complex chemical recovery are serious hurdles to overcome.

Most of the opportunities in Fig. 16 provide yield gains of 3% or less – not so exciting, perhaps, but feasible and operating in some mills. In fact, there are a lot of opportunities which can deliver 1–3% yield gains: additives such as anthraquinone and polysulphide, moving to advanced modes of digester operation, oxygen delignification (especially with a higher kappa target after pulping), and close attention to the quality of chips being fed to a digester. It is also good to have a strong command of existing knowledge and apply it to the technical details of good kraft pulping practice.

Enhanced yields can also come from better chip making and dimensional control, improved pre-steam and impregnation practices, cooking at lower temperatures for longer times wherever possible, minimization of rejects from pulping (and the re-processing of them), efficient fibre spill collection, and tight process control of oxygen delignification and bleaching. Research demonstrates that impressive, cumulative yield gains are possible.

Finally, Fig. 17 is an attempt at reality – what can you do in a kraft mill to improve pulp yield at modest cost with the equipment you have today? The items are listed in order of increasing cost:

- Get out – and stay out – of the residual delignification phase.
- Make your CTS plant perform to maximize the 2–8 (or 9 or 10) mm thick fraction. Minimize the fines going to pulping, and deal effectively with the (small) fraction of overthick material. Buy or make chips with a narrower distribution of thickness.
- Push continually to increase your best species for yield. Know the real numbers by species from R&D work done on your wood sources.
- Make sure that your alkali charge and maximum temperature of cooking don’t creep too high, or your sufficiency too low. Process creep can occur over the long term, and current process targets may lose their connections to the original reasons for change.

Practical To Do At Modest Cost

<table>
<thead>
<tr>
<th>Factors</th>
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<tbody>
<tr>
<td>Stay out of residual delignification phase</td>
</tr>
<tr>
<td>Get full performance from CTS plant</td>
</tr>
<tr>
<td>Optimize for best species in a mixture</td>
</tr>
<tr>
<td>Optimize pulping recipe for EA, Tmax</td>
</tr>
<tr>
<td>Add AQ</td>
</tr>
<tr>
<td>Improve pre-steaming, impregnation regimes</td>
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</table>

Fig. 17. When ranked according to what is practical to do at a modest cost, the top ten factors offer plenty of opportunities for improvement.
• Anthraquinone? It is probably the simplest quick fix for yield gain if you can afford it. Don’t waste it by adding too much, losing some of it in an early black liquor extraction, or failing to recognize trade-offs with other primary factors such as alkali charge, sulphidity, and kappa target.

• Do anything you can to improve chip pre-steaming. Optimize impregnation by ensuring that the ingredients you put in your digester are the best you can provide. Don’t exceed what the chemistry can actually do.

• And if the opportunity comes, go to an advanced batch or continuous digester system and advanced oxygen delignification.

Happy kraft pulping!

References
6. ibid., p.141–150.

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