

The Correlation of COD and Yield in Chemical Pulp Bleaching

Hans U. Süss
Director
Degussa AG
D 63403 Hanau
Germany

John D. Kronis
Technology Manager
Degussa Corp.
Allendale N. J.
USA

1. Abstract

A correlation between the COD of the effluent and the yield loss can be made based on theoretical considerations using the lignin content and the oxidation equivalents applied. These data are compared to the results of experiments with different bleaching sequences. The effect of cellulose oxidation is similarly calculated and the result of an oxidative treatment is measured.

Normal ECF conditions were used to establish a best case scenario. For different oxygen delignified pulps a very similar ratio for the effluent COD and the yield loss was found. The ratio of the COD to the yield loss (both values in kg/t) was found to be 0.9. The application of drastic conditions in the extraction stages combined with high charges of oxygen or hydrogen peroxide produces a higher effluent load and a lower yield. Very high extraction temperature with higher peroxide addition degrades more cellulose. This shifts the COD to yield loss ratio more towards 1. The yield loss increases for oxygen delignified hardwood pulp from 20 kg/t (2%) to 25 kg/t and for softwood pulps from 40 kg/t (4%) to a level of 50 kg/t.

2. Introduction

ECF bleaching seems to become the dominant method to brighten kraft pulps. The work horse in ECF bleaching sequences is chlorine dioxide. It replaces chlorine in the first stage. Divided by extraction stages a chlorine dioxide treatment is typically repeated three times. However, in practice DEDED is not the bleaching sequence of choice. Oxygen and hydrogen peroxide are applied to improve oxidation and extraction and allow cost effective brightening. The conditions in these stages can undergo a wide variation with a significant impact on the chemicals demand. Recently pressurizing of Eo and Eop stages and high temperature were recommended to improve the delignification and bleaching effect. However this increases the COD load [1]. Since this higher effluent load must have a source, it can be the expression of a lower pulp yield.

The costs of bleaching are an important factor in chemical pulp production. Normally the focus is on the costs of the chemicals applied. However, yield, i.e. pulp losses, are also a cost factor. Yield is affected by the bleaching conditions. The target of pulp bleaching is to remove the lignin residual. Bleaching oxidatively decolorizes lignin and depolymerizes it simultaneously into water soluble compounds. The products of the oxidation with chlorine dioxide at an acidic pH have an improved water solubility under alkaline conditions. The sodium salts of carboxylic acids or phenolates are water soluble. The yield decreases with the intensity of lignin solubilisation. In an ideal situation nothing but lignin is dissolved. In reality additional compounds are removed during bleaching. Polyoses, which are chemically bound to the lignin become water soluble with lignin degradation. In addition, aggressive bleaching conditions will not only degrade lignin. They will cause side reactions like the oxidation and extraction of cellulose. More dissolved material will produce a higher effluent load. Thus, yield and effluent load are linked. The effluent load should be an indicator for the yield loss during bleaching. The question is, how close is this correlation of yield and effluent load?

To measure yield on mill scale is difficult. There are too many small differences in the moisture content of the wood, the bark content, the amount of rejects, losses through spills and so on. Even on laboratory scale it is complicated to measure yield. This is especially valid for multistage bleaching processes, where every small error becomes multiplied. It is therefore necessary to run all experiments at least twice. To use the COD to predict an effect on the yield would be much easier. We have decided to run experiments and, in addition, evaluate the possible correlation between COD and yield loss theoretically.

3. Lignin content in unbleached pulp

Knowledge about the lignin content of a pulp allows an estimation of the inevitable yield loss resulting from lignin oxidation and solubilization. A method to estimate the lignin content is to measure Klason lignin. This analytical procedure is rather complicated. It would be advantageous if a more common value for lignin content could be used. The kappa number is the most typical value used in pulp mills for an indirect measurement of the lignin content. Kappa number and lignin were connected closely by Li and Gellerstedt [2]. They have found for the conditions of kappa number analysis, a demand of 12.8 oxidation equivalents (coming from the permanganate) to oxidize one phenylpropane unit. This provides for the calculation of the lignin amount in pulp using the kappa number.

Bleaching changes the number of double bonds in the residual lignin only moderately. The oxygen content only increases in the dissolved part of the lignin; the residual lignin remains nearly unchanged [3, 4]. The error in a calculation of the amount of lignin using the same factor for unbleached and oxygen bleached pulp therefore seems to be rather small. Only for hardwoods does this kind of calculation give incorrect figures because they consume permanganate not only for lignin but also to oxidize double bonds in polyoses. According to Li and Gellerstedt [2] this consumption of permanganate can reach up to 50% of the total amount. The specific consumption of permanganate by these hexenuronic acids is lower; it is only 8.6 OXE per mole. Therefore by weight more pulp will be dissolved at the same kappa number. A calculation using Li's and Gellerstedt's factor for different pulps is made in Table 1.

Table 1: Calculation of the amount of lignin in pulp using the consumption of potassium permanganate in kappa number measurement and Li's factor (12.8 OXE for each phenylpropane unit with an average molecular weight 183 [2]).

pulp type	Kappa #	consumption of KMnO ₄ (mole/kg pulp)	apparent lignin content (g/kg pulp)	Klason Lignin (g/kg)
pine kraft pulp (conv.)	27.7	0.547	39	28.3
spruce/pine kraft pulp (MCC)	22.1	0.447	32	n.d.
eucalyptus kraft pulp	18.4	0.370	26.5	n.d.
spruce kraft pulp, O ₂ del.	15.0	0.299	21	16.9
eucalyptus kraft pulp, O ₂ del.	9.9	0.198	14	8.4
eucalyptus kraft pulp, O ₂ del.	8.4	0.169	12	n.d.

It can be expected that softwood pulps also lose some carbohydrates during bleaching. Therefore the loss of yield during bleaching should in all cases be higher than 3% to 4% for unbleached pulps and higher than 2% for the oxygen bleached pulps. If the yield loss on the other hand becomes significantly higher than those figures, a degradation of the cellulose during bleaching very likely has taken place. These calculated figures are compared with actually measured numbers in chapters 5 to 6.

4. Effluent COD and yield

During bleaching organic compounds are solubilized. Basically any bleaching agent is applied only to initiate oxidation, thus increasing the solubility of the residual lignin. Simultaneously cellulose and polyoses are dissolved in a side reaction. In addition extractives become water soluble. The amount of dissolved organic material in the effluent can be correlated to a decrease of the yield.

The organic compounds in the typical effluent of a bleach plant are nearly totally oxidized with potassium dichromate under the conditions of the COD test [5]. This allows the calculation of the oxygen demand for a known compound. It also allows the calculation of the amount of organic material in an effluent, if the structure ($C_xH_yO_z$) of the organic compound is known. In consequence, the analysis of the COD of a bleaching stage effluent can be a tool to calculate the yield loss in bleaching. The prerequisite is some knowledge about the composition of the cellulose and lignin derivatives in the effluent.

4.1 COD and cellulose

For cellulose the formula $(C_{12}H_{20}O_{10})_n$ can be used for a calculation of the COD. One kg of cellulose requires 1.185 kg of oxygen for a complete oxidation. Thus 1 kg of COD is equivalent to 840 g of cellulose. A cleavage of the cellulose chain during the bleaching process produces molecules with a lower molecular weight and a better solubility. The oxidation of the aldehyde end group to a carbohydrate acid (uronic acid) additionally increases the solubility. One oxidized endgroup in a chain with four or five cellobiose units gives a COD which is very similar to the COD of pure cellulose, because the total oxygen content differs only slightly. Such a product would be water soluble. Only for compounds with longer chains, e. g. six cellobiose units, the oxidation of the aldehyde end group does not produce water soluble products [6]. The oxidation of 10 kg of dissolved cellulose in an effluent requires about 11 kg of oxygen, respectively a COD of 11kg/t is equivalent to a loss of 10 kg substance or 1% yield.

This theoretical calculation was tested with a very hot extraction of fully bleached pulp. A softwood kraft pulp was conventionally bleached, thus the residual lignin was very low. Every compound going into solution should be the product of cellulose degradation by peeling or by oxidation. The data in table 2 do correlate very well with the theory. Hot extraction results in a COD of 30.5 kg/t and a yield loss of 27 kg/t. This ratio of 1.13 is very close to the theoretical value for cellulose. A high intensity oxidation during a hot Eop treatment oxidizes the extracted material and with increasing oxygen content the COD/yield ratio becomes lower. The ratio falls to 1.07. The hot oxidative treatment not only degrades the dissolved part of the pulp, the viscosity of the residual becomes lower.

Table 2: Extraction and oxidation of fully-bleached softwood kraft pulp (viscosity 14.3 mPa's) with caustic soda (2% NaOH) compared to Eop (2% NaOH, 2% H₂O₂, 0,3 MPa O₂). Trials at: 10% cons., 98°C, 2% NaOH, 1h.

treatment	yield (%)	yield loss (kg/t)	viscosity (mPa's)	COD (kg/t)	COD/yield loss (kg/t:kg/t)
E	97.3	27	14.0	30.5	1.13
EOP	97.4	26	9.3	27.7	1.07

Unbleached sulfite pulp is rich in hemicelluloses. If treated only with alkali, dominantly the low molecular weight polyoses become water soluble. An extraction with caustic soda will not influence the chemical composition of the compounds. Thus the ratio of COD to yield should be very close to 1.1. Figure 1 shows a comparison of the values for COD and yield for the extraction of a beech sulfite pulp. The resulting straight line correlates very well with literature, which describes a linear effect of the NaOH concentration on the yield for the production of dissolving pulps [6].

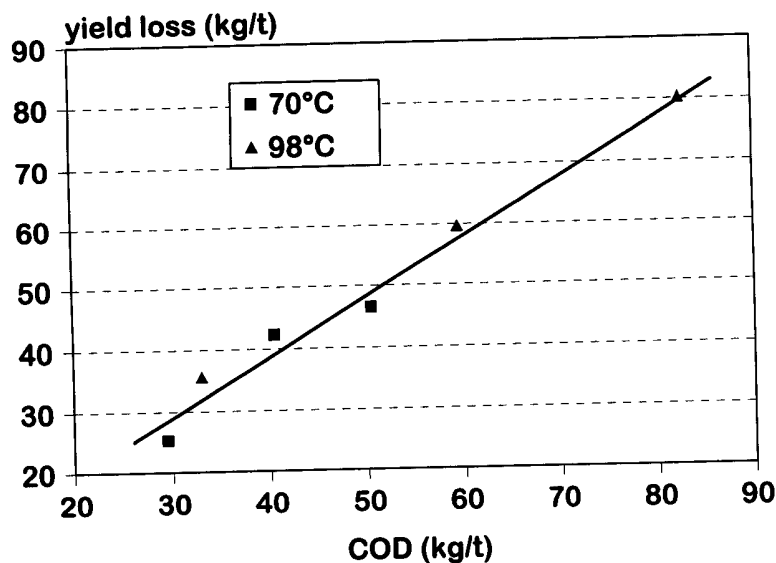


Figure 1: Effect of caustic soda concentration and temperature on COD and yield for beech sulfite pulp. Extraction with 1%, 2% and 3% NaOH at 10% cons., 70°C and 98°C. The line gives a ratio of 1.03 for COD to yield.

The extraction not only eliminates polyoses but simultaneously lignin [8]. This becomes visible as a kappa number drop. Table 3 has data for the extraction of sulfite pulps with different levels of lignin. The solubility of the sulfonated lignin residual becomes visible in the higher ratio for COD to yield loss. The COD of sulfite lignin is lower compared to the COD of kraft lignin (see below) because of its higher oxygen content. Fengel [9] reported a composition of sulfite lignins which translates in an oxygen demand of 1.338 kg and 1.540 kg per kg lignin (spruce and beech lignin, resp.).

Table 3: Extraction of sulfite pulps with caustic soda, effect of Kappa number and temperature. Constant 2% NaOH, 10% cons.

pulp type	temp. (°C)	Kappa, extracted	yield (%)	yield loss (kg/t)	COD (kg/t)	COD/yield loss (kg/t :kg/t)
spruce magnefite, kappa 28.5	70	24.2	97.0	30	38.4	1.28
beech, acid sulfite, kappa 15,6	98	11.5	94.1	59	59.5	1.01

* It can be expected that a moderate oxidation of cellulose or polyoses is sufficient to produce partially water soluble products. A small increase of the oxygen content of these compounds will not change the COD to yield ratio significantly. It will remain very close to 1 or 1.1.

4.2 COD and lignin

A calculation of the COD for lignin is a bit more complicated. The residual of lignin is continuously modified and oxidized during the bleaching process. In consequence, the amount of oxygen in the formula is increasing with ongoing delignification. The chemical composition of kraft lignin is approximately $(C_9 H_{9.7} O_{3.3})_n$ [9]. The

corresponding COD is 1.850 kg per kg kraft lignin or 1 kg of COD is equivalent to 540 g of kraft lignin. This COD is significantly higher than the COD caused by cellulose compounds. However, during bleaching the oxygen content of the lignin is increased.

An estimation of the oxygen content increase of the lignin can be made using the amount of residual lignin and the amount of oxygen added with the bleaching agents. One option is to calculate the oxygen increase of the lignin with the assumption that the bleaching chemicals do react only with lignin. Such a calculation is made in Table 4. The conditions selected for these experiments were high kappa factors in the D stages (0.3 in D₀, 0.5 in D₁) and low temperature (70°C) and low NaOH charge in E (1.5%). The input of oxygen equivalents therefore was on the high side.

Table 4: Calculated increase of the oxygen content of softwood kraft lignin in ECF bleaching sequences. MCC pulp (Kappa 22.1) sequence DEpDPD; oxygen bleached pulp (Kappa 16.9) DEopDPD, the amount of oxygen consumed in the Eop stage was assumed

Kappa #	ClO ₂ (act. Cl) (%)	H ₂ O ₂ (%)	O ₂ (%)	oxygen equivalents (g/kg)	calculated lignin content (g/kg)	kraft lignin formula	oxidized lignin formula
16.9	5.62	0.9	0.2	18.9	25	C ₉ H _{9,7} O _{3,3}	C ₉ H _{9,7} O _{11,3}
22.1	9.63	1.0	-	26.5	32	C ₉ H _{9,7} O _{3,3}	C ₉ H _{9,7} O _{12,1}

It is rather difficult to imagine a lignin structure with such a high oxygen content. If each carbon atom is bound in average to 1.3 oxygen atoms, the resulting molecule should be rather unstable, it should decompose into smaller fragments. On the other hand it is well known that the effluent of the first two bleaching stages contains compounds with a rather high molecular weight [10]. This discrepancy arises from the very simplified approach for the calculation. First of all it can be expected that some of the active oxygen applied will be consumed in side reactions, e.g. with aldehyde end groups of the cellulose. Secondly, the oxidation of the lignin will certainly increase stepwise with the number of bleaching stages. Thus, the molecular weight of the dissolved lignin will become significantly lower in the later bleaching stages. An indication for this effect is the increasing lighter color of the effluent, which can be correlated to a decrease of conjugated structures.

The resulting formula for the oxidized lignin can be used for a calculation of the COD remaining in the effluent after the oxidation in bleaching. This remaining oxygen demand of a molecule with the formula C₉ H_{9,7} O_{11,3} is only 620 g per kg. This is less than half of the COD for unbleached kraft lignin. This value will be compared to the data measured in the next chapter.

Pulp contains not only cellulose, polyoses and lignin. Bleaching solubilizes also extractives, lignans and tannins. Their amount can be significant, especially in hardwood pulps [11]. However, extractives or related compounds are chemically close relatives to lignin. They are therefore in this very rough approach treated as "lignin".

* The intense oxidation of lignin in conventional or ECF bleaching results in a significant increase of its oxygen content. Thus the ratio between COD and yield will start at a high COD for a given yield loss and drop during bleaching. Oxygen delignification will have a ratio on the high side (>>1.3). The average ratio for the full sequence can be well below 1.

5.1 Yield in conventional ECF bleaching

The considerations about lignin so far were totally theoretical. The only proof for these speculations is an actual comparison of COD and yield. As the first examples, ECF sequences with normal (high) chlorine dioxide input and

moderate conditions in the extraction stages were selected. It is a well accepted standard to apply hydrogen peroxide and oxygen in the first extraction stage in order to increase lignin extraction and lift the brightness. This overcomes the lower delignification ability of ClO₂ compared with chlorine. The additional oxidation in this Eop stage allows lowering the amount of caustic soda. It is still less typical to use hydrogen peroxide in the second E stage. The economical advantage of such an addition is depending on the price level for chlorine dioxide and hydrogen peroxide. The replacement ratio achieved for ClO₂ with H₂O₂ is much better than just stoichiometric, hydrogen peroxide application is normally very cost effective. Table 5 lists the demand for chemicals bleaching a softwood pulp with the sequence DEoDED and compares these results to bleaching with DEopDEpD.

Table 5: Chemicals demand for ECF bleaching with only ClO₂ and bleaching with oxidative supported E stages, softwood kraft pulp, oxygen del. to Kappa 15, final brightness 90⁺ (%ISO)

sequence	total act Cl (%)	total NaOH (%)	E stage temp. (°C)	H ₂ O ₂ (%)	COD (kg/t)	yield (%)
DEoDED	7.53	2.3	75	--	37.3	96,1
DEopDEpD	5.52	2.1	75	0.65	37.5	96,1

In terms of the COD produced and the total yield, the results do not indicate any difference of significance between both sequences. The COD to yield loss ratio is 0.96. This indicates an oxidation of the lignin content well below the theoretical maximum.

Table 6 lists the results bleaching other softwood and hardwood kraft pulps with a shorter sequence. The total yield loss is about twice as high as the calculated number for the amount of lignin (see table 1). This higher loss was expected, because polyoses are dissolved during bleaching. The softwood pulps have a COD to yield loss ratio below 1. The compounds dissolved during bleaching seem to be a mixture of highly oxidized lignin and polyoses. The hardwood pulps do have a higher content of easily solubilized polyoses. Therefore the ratio for COD to yield loss is very close to 1. These data are rather close to the level expected from the theoretical considerations.

Table 6: Effect of ECF bleaching of kraft pulp on COD and yield. Moderate conditions in the E stages (75°C) kappa factor in D₀ 0.2, final brightness 90 %ISO, double tests (if not otherwise stated)

pulp type	Kappa #	sequence	yield (%)	yield loss (kg/t)	COD (kg/t)	ratio COD/loss (kg/t:kg/t)
scand. pine/spruce, O ₂ del.	17.0	DEopDP	95.17*	48.3	41.8*	0.87
centr. europ. spruce/pine O ₂ del.	15.0	DEpDP	95.98	40.2	37.8	0.94
braz. eucalyptus	18.4	DEopDP	96.53	34,7	36.3	1.05
braz. eucalyptus O ₂ del.	8.8	DEopDP	98.1	19	18.6	0.98

* triple measurement, standard deviation: yield ± 0.05; COD ± 1.1

5.2 Yield in bleaching with hot oxidative E stages

The application of high temperature and high charges of caustic soda and hydrogen peroxide was recently recommended to increase the effects of delignification and brightening in the extraction stages [1, 12, 13]. This would allow ECF sequences to be run with very low chlorine dioxide input. The potential savings of ClO₂ are

pronounced. Table 7 compares the demand for chemicals in conventional ECF bleaching to a modified hot Eop and P(O) treatment.

Table 7: Shift in conditions and demand for bleaching chemicals in ECF bleaching of eucalyptus kraft pulp (Kappa 17) using normal or hot conditions in the first and second E stage.

sequence	total act Cl (%)	total H ₂ O ₂ (%)	Eop temp. (°C)	P temp. (°C)	viscosity (mPa·s)	COD (kg/t)
DEopDD	5.01	0.3	80	--	28.4	42
DEopDP	3.86	0.45	80	75	27.1	43
DEopDP(O)	2.45	1.0	100	110	18.7	54

The active chlorine demand is cut by more than 50%. However, the hot extraction stages do produce a higher COD. This effect is known [1], but was only recently correlated to the pulp yield [14]. Table 8 contains these data. In these experiments the temperature in the hot P stages was limited to 98°C. This allowed the use of PE bags and excluded the possibility of a contamination of the sample with metal traces from a reactor wall. (Even though this would be rather unlikely if thoroughly passivated stainless steel equipment is used.)

The drastic conditions again produce a higher COD. The yield is lower compared with moderate conditions. Bleaching to full brightness results in very similar lignin levels in the bleached pulp. Thus the higher yield loss has to be the result of cellulose degradation. Because degraded cellulose has a COD which does not differ very much from normal cellulose (see part 4.1), the COD to yield loss ratio of this dissolved material is very close to the theoretical COD of pure cellulose. Thus also for these drastic conditions with higher yield losses the ratio between COD and yield loss remains nearly the same.

Table 8: ECF bleaching of kraft pulps with hot E stages, effect on COD and yield. Kappa factor 0.1 in D₀, temperature in Ep, Eop and P stages 98°C, bleaching to 90 %ISO

pulp type	Kappa #	sequence	yield (%)	yield loss (kg/t)	COD (kg/t)	ratio COD/loss (kg/t:kg/t)
centr. europ. spruce/pine O ₂ del.	15.0	DEpDP	95.15	48.5	44	0.91
braz. eucalyptus	18.4	DEopDP	95.1	49	51.1	1.04
braz. eucalyptus, O ₂ del.	8.8	DEopDP	97.7	23	22.2	0.97

In an E stage application of H₂O₂, a temperature increase is required to consume peroxide amounts that are higher than the typically applied 0.5% H₂O₂. This temperature increase is necessary to accelerate the consumption. The effects of the addition of higher amounts of hydrogen peroxide with a simultaneous increase of the temperature on pulp parameters and COD are described in Figures 2 and 3. The Figures illustrate the advantage of higher H₂O₂ amounts on brightness and delignification. Brightness increase and kappa drop are significant up to approximately 90°C, then the effects fade off. In addition, above a temperature of approximately 90°C the COD starts to increase sharply. Therefore at very high temperature the advantage of the addition of hydrogen peroxide is altered into a disadvantage, at least in terms of yield.

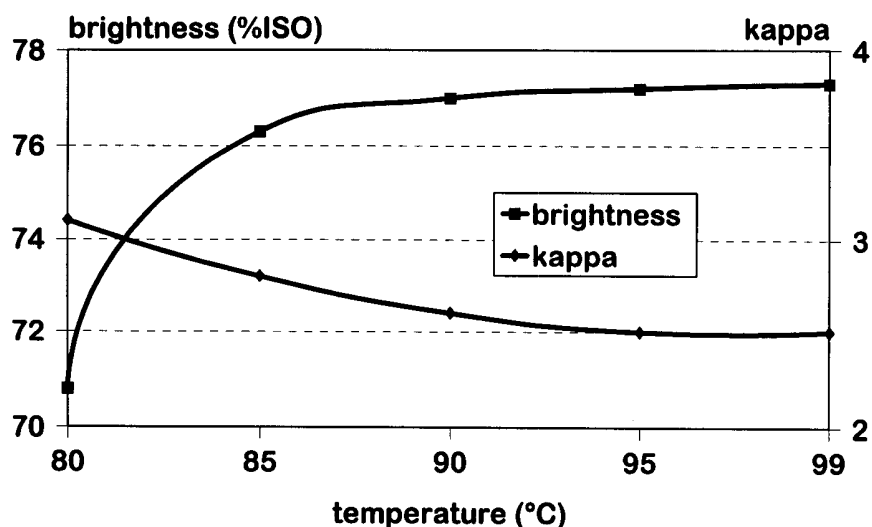


Figure 2: Brightness increase and kappa drop with temperature in D_0Eop bleaching of softwood kraft pulp. Do stage with 3 % ClO_2 (kappa factor 0,2) at 50°C, 1h. Eop stage with 0,5% (80°C), 0,75% (85°C and 90°C), and 1% H_2O_2 (95°C and 99°C).

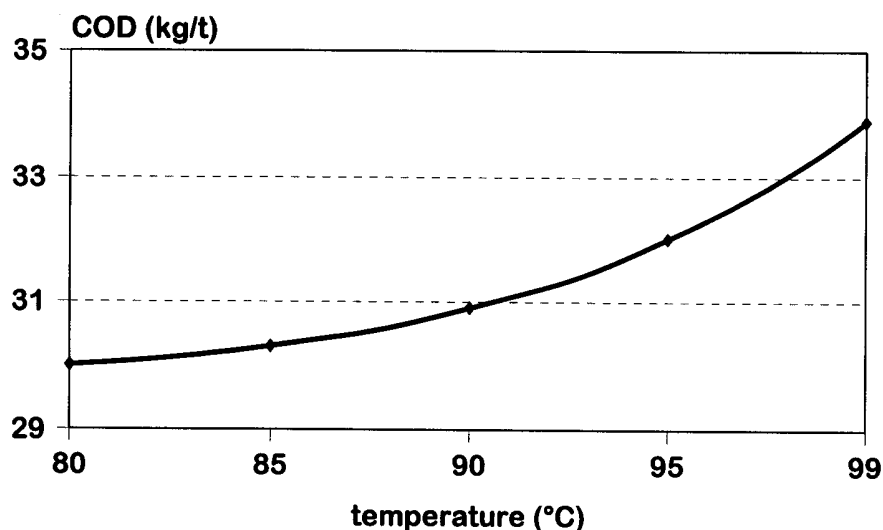


Figure 3: Increase of COD with increasing temperature bleaching of oxygen delignified softwood kraft pulp. Sequence OD_0Eop . Conditions for Eop stage see figure 2.

6. Conclusions

* ECF bleaching:

For bleaching oxygen delignified kraft pulps to full brightness in multistage sequences a ratio between the effluent COD and the yield loss in bleaching has been found:

High levels of chlorine dioxide and moderate conditions in the extraction stages produce a significant increase of the oxygen content of the lignin. Bleaching eliminates only moderate amounts of polyoses or cellulose. The ratio between COD and yield loss is below 1. These conditions produce the highest yield.

High temperature in E stages combined with high NaOH and H₂O₂ addition results in cellulose degradation. The COD to yield loss ratio increases to about 1. The yield is lower.

* **COD:**

COD values for the effluent of a bleaching sequence can be used to predict the yield of a bleaching process. As a rule of thumb following values can be used:

ECF sequences: ratio (COD/yield loss) about 0.9 to 1.

* **Peroxide application:**

The addition of H₂O₂ results in overall benefits (brightness and delignification) within the temperature range of 75°C to 90°C. A higher level impairs these advantages because of the COD increase.

8. Experimental

All trials were run with well washed commercially produced kraft pulps. D, E, and P stages were run in sealed PE bags at 10% consistency with variation of time and temperature. All pulp samples were preheated to the bleaching temperature and all the chemicals were added at once and mixed thoroughly with the pulp.

Pressurized peroxide stages and Eop stages were conducted either in a laboratory scale stainless steel high shear mixer at 10% consistency using 250g of absolute dry pulp. Oxygen pressure was 0.3 MPa. For yield analysis the Eop stages were run with 50g fluffed pulp at 15% cons. in a thoroughly passivated stainless steel autoclave at 0.3 MPa oxygen pressure. Yield was analyzed weighing the full sample after drying. Yield data are given as the mean value of at least two experiments run in parallel.

Brightness, etc. were measured according to TAPPI standards. Klason lignin was measured using TAPPI standard T 222 for acid insoluble lignin. After each bleaching stage the pulps were repulped to 2% cons. with tap water. No additional washing water was applied. An effluent sample was taken from the filtrate and COD was determined according to Zellcheming Merkblatt X/2/76. Any excess of hydrogen peroxide was decomposed with catalase before analysis. Bleaching sequences are described using the CPPA glossary.

9. References

1. J. Devenyns, A. Renders, J. Carlier, P. Walsh, Optimal use of hydrogen peroxide to design low AOX ECF sequences; *Tappi 1995 Pulping Conf. Proceedings*, 281 - 288
2. J. Li, G. Gellerstedt; On the structural significance of kappa number measurement; *Int. Symposium on Wood and Pulping Chem. Montreal, 1997*, Proceedings G1-1 - G1-4
3. G. Gellerstedt, K. Gustavson, E. L. Lindfors, D. Robert; The structural modification of lignin in bleaching, *Proceedings, 1989 Intn. Symposium on Wood and Pulping Chemistry*, Raleigh, NC 211 - 215,
4. G. Gellerstedt, L. Heuts; Changes in the lignin structure during a totally chlorine free bleaching sequence; *J. Pulp & Paper Sc.* 23 (7) J335 - J340 (1997)
5. L. Göttching, H.-L. Dalpke, H. von der Heyde; Über die Bestimmung von CSB, BSB und TOC am Filtrat von Suspensionen aus Halbstoff, Papier und Altpapier, *Papier* 31, (1) 1 -11 (1977); R. Wagner; Die CSB-Methodik im Abwasserabgabengesetz; *Vom Wasser*, 46, 139 - 160 (1976)
6. J. Puls, Universität Hamburg, personal information

7. S. A. Rydholm, *Pulping Processes*; ISBN 0 471 74793 9 Interscience Publ., New York, (1965) p 1006
8. H. U. Süss, H. Krüger; Die Zellstoffbleiche mit Peroxid unter neuen Aspekten, *Papier*, **35** (10A) V 25 - 32 (1982)
9. D. Fengel and G. Wegener; *Wood*; ISBN 3-11-008481-3 (1983), p 152
10. K. Kringstad, K. Lindström; Spent Liquors from Pulp Bleaching; *Enviro. Sci. Technol.* **18** (1984) (8) 236 - 238A
11. J. Basta, G. Wäne, S. Herstad-Svärd; Partial closure in modern bleaching sequences - Eucalyptus pulp; *ABTCP meeting 1996*, preprints 155 - 161
12. R. Reeves, R. Boman, S. Nordén; Impact of sequence position for pressurized (PO) stage in ECF bleaching; *Tappi 1995 Pulping Conf. Proceedings*, 263 - 267
13. L. Sjödin, S. Nordén and R. Boman; Extended Delignification with Oxygen and Hydrogen Peroxide in ECF and TCF Sequences, *Tappi 1994 Pulping Conf. Proceedings*, 21 - 27
14. H. U. Süss, N. Nimmerfroh, J. D. Kronis, The naked truth on hot peroxide bleaching, *1997 CPPA annual meeting, preprints B* 129 - 136