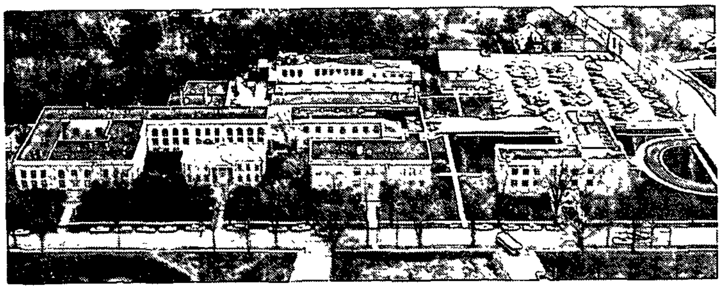

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ABSTRACT

Oxygen bleaching and pulping to unusually low unbleached kappa numbers are distinct process modifications which have similar beneficial effects on kraft bleach plant pollutant production and chemical costs. This suggests that the two technologies may either be interchangeable or capable of being combined to have a significantly greater impact than either one alone. This study was undertaken to test both possibilities. It was concluded that southern pine can be pulped to kappa number 15 and subsequently bleached in the C_DED sequence to give a pulp equivalent in brightness and strength to a conventional 35 kappa pulp fully bleached in the OC_DED sequence. When low-lignin pulping is combined with an OC_DED bleach, chemical costs and effluent loadings can be sharply reduced. These reductions are disproportionately greater than the reduction in unbleached kappa number.

INTRODUCTION

The attractiveness of oxygen bleaching for softwood bleached kraft mills lies in its ability to selectively remove about half of the lignin from the unbleached pulp without significantly contributing to pollution loadings. This results in a substantial reduction in the amount of pollutants generated in the conventional part of the bleach plant. It has the added benefit of reducing bleaching chemical costs, since chlorine and caustic requirements are halved and the charge of chlorine dioxide can often be reduced.

Recently, interest has been expressed in the possibility of kraft pulping to unusually low unbleached lignin contents. This can be accomplished by direct intervention in the process to modify the time profiles of the cooking chemical concentrations (1,2) or, more simply, by adjusting white liquor composition and cooking conditions (3). The effect is similar to that of oxygen bleaching - a decrease in the amount of lignin entering the bleach plant with attendant reductions in pollutant production and chemical costs. In view of this, the question arises as to whether a mill in need of the benefits of oxygen bleaching might consider a conversion to low-lignin pulping as a less costly alternative. Increasingly stringent pollution abatement requirements give rise to a related question: Can low-lignin pulping be coupled with oxygen bleaching to achieve these benefits to a greater extent than is possible with either technology alone? To provide preliminary answers to both questions, we undertook a laboratory study and describe the results here.

Conventional and low-lignin pulping conditions were used to prepare kraft pulps in the laboratory from southern yellow pine. The low-lignin pulping conditions employed were identified in an earlier optimization study (3) and subsequently by similar methods. All pulps were bleached in the OC_DED sequence. The control pulp was also bleached in the C_DEDED sequence and one of the low-lignin pulps in the C_DED sequence. The optical and physical properties of both the unbleached and bleached pulps were measured, and effluent properties were determined.

RESULTS AND DISCUSSION

The pulping conditions and unbleached pulp properties are contained in Tables 1 and 2, respectively. The conditions were chosen to represent a variety of approaches to obtaining low kappa number unbleached pulps and are not necessarily optimal from the economic point of view. Economic optimization will result in cost-reducing modifications which are, however, unlikely to result in large changes in unbleached pulp properties or bleach response. In the preparation of the pulp labeled MKA-30, for example, the high anthraquinone (AQ) charge can probably be reduced without incurring either a very great increase in kappa number or a marked change in bleach response.

Replacement of the Oxygen Stage

The combined use of anthraquinone addition and high sulfidity allows low kappa numbers to be achieved at satisfactory viscosity and yield levels. If the effective alkali (EA) charge is simultaneously increased, no increase in cooking time is necessary to achieve the greater degree of delignification. This can be seen by comparing the data in Table 1 and 2 for the pulps designated CK, MKA-30 and MKA-20. The most extensively delignified of these, pulp MKA-20, had viscosity and kappa number characteristics comparable to those of an oxygen-bleached conventional kraft (CK). Accordingly, it was subjected to C_DED bleaching, and the results were compared with those obtained by OC_DED bleaching of CK, as shown in Table 3 and Fig. 1. The C_DED sequence applied to the low-lignin pulp produces a fully bleached pulp very similar to that obtained by the (CK)-OC_DED sequence. With 0.4% more ClO_2, the former sequence produces equivalent brightness at a yield, based on wood, which is 1.2% lower (assuming equivalent shrinkage per unit of kappa number reduction in the conventional stages).

Table 4 shows that the two bleached pulps had nearly identical physical properties in spite of the distinctly superior tear strength of CK when both were in the unbleached state. This advantage was lost in the oxygen stage.

Combined Low-lignin Pulping and Oxygen Bleaching

To evaluate the effectiveness and technical feasibility of combining the two technologies, the response of the pulps of Table 2 to oxygen bleaching was studied, and the pulps were subsequently bleached in the OC_DED sequence. As shown in Fig. 2, the low-lignin pulps exhibited normal delignification behavior in a high-consistency oxygen stage. Application of 3% NaOH resulted in kappa number reductions ranging from 53 to 60% compared with 52% for CK. Viscosity retention was more variable, as Fig. 3 shows. The kraft pulps having unbleached viscosities in excess of 30 cp were most prone to degradation. Pulps CK and MK-30 underwent viscosity reductions of 39 and 46%, respectively, when 3% NaOH was applied; for the other pulps the corresponding reductions were in the range 26-29%. It is notable that pulp MKA-30 underwent such a moderate viscosity loss, although the unbleached value was a relatively high 27 cp. Retention of yield paralleled that of viscosity, as shown in Fig. 4. Carbohydrate losses were smallest for MKA-30 and MK-20 and somewhat larger for CK and MK-30.

The practical implications of these results are more readily evident from Fig. 5 and 6. The former shows that, at a given kappa number after the oxygen stage, pulps MK-30 and MKA-30 have significantly higher viscosities than conventional kraft. Stated differently, these pulps have significantly lower postoxygen stage kappa numbers than the conventional pulp at any given viscosity. The low-lignin pulps of initially lower viscosity, MK-20 and MKA-20, also have lower viscosity at fixed postoxygen kappa number. Extrapolation of the CK line on the graph suggests that they would not be significantly better than conventional pulp except possibly at very low kappa numbers. Similar conclusions may be drawn from the yield-kappa number relationships, which are presented in Fig. 6. In terms of yield, however, there is a clear superiority of MKA-30 over MK-30, and there is a stronger suggestion that the lower viscosity low-lignin pulps are better than very extensively oxygen-delignified conventional kraft.

On the basis of the above experimental results, appropriate levels of caustic application were selected for each pulp, and all were fully bleached in the sequence OC_DED. Several levels of ClO_2 were applied in each case. The results are shown in Table 5 and may be compared with those shown in Table 3 for the conventional pulp. The two low-lignin kraft pulps responded similarly, as further illustrated in Fig. 7. It is apparent that these pulps can be bleached to higher brightness than the conventional pulp and that a given brightness in the range 86-88 can be reached with a significantly smaller amount of ClO_2 than in the case of the conventional pulp. The low-lignin kraft-AQ pulps, MKA-30 and MKA-20, had about the same brightness ceiling as the conventional pulp but required substantially less ClO_2 to reach values in the 86-88 brightness range (Fig. 8). The reduction in ClO_2 requirement did, however, depend on the kappa number after the oxygen-stage being sufficiently low, as shown by the brightness decrease at low ClO_2 charges when the caustic charge in the oxygen stage was decreased (Table 5). Another low-lignin kraft-AQ pulping option, involving a long, low-temperature cook and moderate AQ charge, gave a pulp (MKA2-30) having a bleach response almost identical to that of the conventional pulp. Since the kappa number of this pulp after the oxygen stage was higher than in the case of any of the other kraft-AQ pulps, this, together with the previous observation, suggests that the bleached brightness of the kraft-AQ pulps is sensitive to oxygen stage kappa number over the range 6-11.

The viscosities of the fully bleached pulps of Table 5 were in certain cases somewhat lower than what might be considered acceptable. To determine the extent to which this was reflected in pulp strength, the physical properties of the pulps were measured, with the results shown in Table 6. Once again, substantial differences were noted among the unbleached pulp strengths, but those of the bleached pulps did not differ as widely. The latter could be divided into two groups: those with viscosities of 14 or less and all the rest. The first group was only marginally inferior in terms of tearing resistance at fixed tensile strength, ultimate tensile, and zero-span tensile. It was composed of the low-lignin pulps having unbleached viscosities near 20 cp.

Table 7 gives the results of BOD determinations on effluents from bleaching the pulps listed in Table 6. The total contribution of the bleach plant to raw mill effluent BOD may be estimated as the sum of the contributions of the individual stages after the oxygen stage. This is apparent from a comparison of the BOD values for the combined effluents with the values obtained by summing the contributions of the individual stages in the MK-20 and MKA-20 cases. The data indicate that, relative to conventional practice, BOD is reduced 54% by oxygen bleaching alone and from 80-85% by oxygen bleaching and low-lignin pulping combined. All low-lignin pulping alternatives gave similar postoxygen BOD values.

The corresponding effluent color data are given in Table 8. The summed contributions of the stages after the oxygen stage indicate that oxygen bleaching reduces color by about 40% and the combination of low-lignin pulping and oxygen bleaching results in color reductions of 70-85%. Comparison of the summed values with values obtained by analysis of mixed effluents suggests that the color values, unlike those for BOD, are not additive. The above conclusion remains valid if, as seems likely, it can be assumed that the degree of nonadditivity is roughly the same for all sequences.

Economics

The major elements entering into the economic evaluation of a proposal to employ combined low-lignin pulping and oxygen bleaching will be the following: reduction in bleaching chemical costs, reduction in cost of effluent treatment to remove BOD, value of effluent color reduction, value of improved energy recovery due to higher recycle of organic material to the recovery furnace, savings due to easier rejects handling, value or cost of change in bleached pulp yield, cost of using higher EA and sulfidity charges and, depending on the strategy adopted, possible costs for AQ and/or increased digester capacity. Low-lignin pulping as an alternative to oxygen bleaching could also be credited with the savings realized by not installing the oxygen stage and by converting from a 5-stage to a 3-stage sequence.

The partial analysis presented in Table 9 is incomplete in two respects: it does not consider many of the elements listed above, and it is based on pulping conditions which have not been cost-optimized. Nevertheless, it does give an approximate idea of the relative magnitudes of the bleaching cost savings and yield penalties. A more complete analysis is in progress.

CONCLUSIONS

1. Southern pine can be pulped to kappa number 15 and subsequently bleached in the C_DED sequence to give a pulp equivalent in brightness and strength to a conventional 35 kappa pulp fully bleached in the OC_DED sequence. The lower unbleached lignin content is achieved with no increase in cooking time by employing anthraquinone together with increased levels of effective alkali and sulfidity.

2. Pulping to low lignin contents by appropriately changing liquor composition markedly reduces bleaching chemical requirements. When the low-lignin pulps are bleached in an oxygen stage, the subsequent bleach response is better than that of oxygen-bleached conventional pulps. This results in a reduction in the requirement for chlorine dioxide in addition to the expected reductions in chlorine and caustic.

3. Low-lignin pulps delignify normally in an oxygen stage, the percentage reduction in kappa number being independent of the unbleached kappa number. Selectivity, with reference to both viscosity and yield, depends on the pulping conditions. Certain of the low-lignin pulping strategies employed give pulps which were more resistant than a control pulp to oxygen-stage viscosity and yield losses.

4. Very substantial reductions in bleach plant effluent BOD and color are achieved by combinations of low-lignin pulping and oxygen bleaching. Reductions of 85% in both appear to be technically possible.

5. Unbleached pulps can be prepared with kappa numbers as low as 19 and bleached strength properties which are virtually identical to those of a 35 kappa kraft control. Kappa number 15 pulps can be made which are only marginally inferior to the control.

EXPERIMENTAL

Southern yellow pine logs were hand debarked, chipped in a Carthage chipper, and screened on a Sweco vibratory screen. Accepts passed a 3/4-inch screen and were retained on a 1/4-inch screen.

Pulping was carried out in a stainless steel digester of approximately 72 liters capacity, fitted with a chip basket, external circulation, and indirect heating. Cooking liquors were prepared from solutions of sodium hydroxide and sodium sulfide of known concentration and density. AQ was added in solid form to the chips in the digester. The pulping conditions employed are shown in Table 1. At the end of the cook, the pressure was slowly relieved to 80 psi, and the blow valve was opened to expel the liquor through a cyclone separator into a muslin-covered wash box, where any entrained pulp was collected. The cooked chips were washed in the digester, then removed and fiberized under a Williams disintegrator.

Cook No. 107 was performed in a set of stainless steel bombs, each of 500-mL capacity, which were heated by rotating them in a thermostatically controlled oil bath. At the end of the cook the bombs were rapidly cooled by spraying them successively with steam and cold water.

The pulp was screened through a 0.008-inch slotted screen plate on a Valley flat screen. The rejects were oven dried, weighed and discarded. The pulp was centrifuged and crumbed, and its consistency was determined in triplicate for calculation of the yield.

Bleaching was carried out in polyester bags. After the bleaching chemicals and dilution water were added, the bag was sealed, kneaded to throughly mix the chemicals with the pulp, quickly heated to the reaction temperature in a microwave oven, and placed in a thermostatted bath. The conditions used are noted below the appropriate data tables. In most cases, washer inefficiency was simulated by carrying over a specified fraction of the effluent from one stage to the next.

Kappa number determinations were done according to TAPPI Standard T 236. Viscosity and brightness were determined according to the TAPPI Standard T 231 and T 452, respectively. Reverted brightness was measured after heating the brightness tabs for 1 hour at 105°C. Pulp processing was by PFI mill, and handsheet properties were determined by TAPPI Standard Methods.

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Table 1 Pulping conditions[a]

Pulp Type	Nominal (Target) Viscosity	Pulp Type Designation[b]	Cook No.	Effective Alkali, %	Sulfidity, %	Liquor-to-wood Ratio, cc/gm	Maximum Temperature, °C	H Factor	Anthraquinone, %
Conventional kraft	30	CK	75 78 121	16.0	25	4.0	173	2000	0
Minimum kappa kraft	30	MK-30	110	19.2	39.9	5.0	173	1810	0
	20	MK-20	115	21.1	36.6	4.1	173	1700	0
Minimum kappa kraft-AQ	30	MKA-30	107	17.5	36.1	4.0	173	1540	0.3
	30	MKA2-30	131	18.2	40.0	4.9	162	1760	0.1
	20	MKA-20	77 116	20.0	38.0	4.0	173	2000	0.2

[a]All percentages based on wood, except sulfidity (based on active alkali).

[b]CK = conventional kraft; MK denotes conditions designed to minimize kappa number subject to a constraint on 0.5% CED viscosity, which appears as a numerical suffix; A denotes anthraquinone addition.

Table 2 Unbleached pulp characteristics

Pulp Type	Cook No.	Screened Yield, %	Rejects, %	Kappa Number	Viscosity, cp	Carbohydrate Yield, %
CK	75	46.4	0.36	34.0	30.9	44.1
	78	46.5	0.34	35.1	32.8	44.0
	121	46.3	0.53	35.3	35.4	43.8
MK-30	110	45.4	0.08	22.6	32.8	43.9
MK-20	115	43.2	0.06	17.8	18.6	42.1
MKA-30	107	45.7	0.08	19.0	27.0	44.4
MKA2-30	131	45.8	0.12	21.3	33.1	44.3
MKA-20	77	43.4	0.04	15.4	18.6	42.4
	116	43.5	0.14	15.6	17.6	42.5

Table 3 C_DED bleaching of low-lignin kraft-AQ pulp compared with OC_DED bleaching of conventional kraft[a]

	Before C_D Stage			E Stage		D Stage						
Sequence	Kappa No.	Viscosity, cp	Yield, % wood	$KMnO_4$ No.	Viscosity, cp	ClO_2,[b] %	Residual, %	NaOH,[b] %	Final pH	Brightness	PC Number	Viscosity, cp
(CK)-OC_DED	18.8	21.8	45.0	2.8	20.6	0.8	0	0.4	3.5	85.2	1.08	--[c]
						1.2	0.16	0.8	4.9	87.2	0.87	--[c]
						1.6	0.27	0.8	4.2	88.2	0.69	17.9
(MKA-20)-C_DED	15.4	18.6	43.4	2.9	16.8	0.8	0	0.4	3.3	82.6	1.05	16.2
						1.2		0.4	2.4	85.5	0.77	16.0
						1.6		0.8	4.0	87.1	0.78	14.0

[a]Conditions: Oxygen (O) 30 min, 110°C, 27% consistency, 100 psig O_2, 0.1% Mg^{++}, 2.2% NaOH.
Chlorination (C_D) 45 min, 25°C, 3% consistency, % Cl_2 (incl. equiv. of ClO_2) = 0.23 x kappa, 15% replacement of Cl_2 with equiv. ClO_2.
Extraction (E) 60 min, 60°C, 10% consistency, % NaOH = 0.5 x total equivalent Cl_2.
Chlorine Dioxide (D) 180 min, 70°C, 10% consistency; at each level of ClO_2 addition, bleaches were run with 0, 0.2, 0.4, and 0.8% of added NaOH; brightness values shown were obtained at the optimum level of NaOH addition.

[b]Chemical charges based on o.d. oxygen-bleached or unbleached pulp wt., depending on the sequence.

[c]Not determined.

Table 4 Comparison of pulp strengths: (CK)-OC_DED *vs*. (MKA-20)-C_DED[a,b]

	(CK)-OC_DED				(MKA-20)-C_DED			
	Viscosity, cp	Tear at 9 km Tensile B.L.	Tensile B.L. at 400 CSF	Maximum Zero-span B.L., km[c]	Viscosity, cp	Tear at 9 km Tensile B.L.	Tensile B.L. at 400 CSF	Maximum zero-span B.L., km[c]
Unbleached	32.8	175	10.3	20.7	18.6	150 145	10.1 10.4	20.7 20.1
After O-stage	20.8	160	10.7	20.8				
Bleached	17.8	155	10.6	20.4	15.9	155	10.3	20.2

[a]Bleaching conditions as in Table 3; the amount of ClO_2 used in the last stage was in each case the minimum amount required to reach a brightness of 87.5 as determined in the experiments of Table 3.
[b]The pulps were beaten in a PFI mill to 5 different freeness levels in the range 750-350 CSF.
[c]Zero-span tensile breaking length was measured at each beating interval; the value shown is the highest of those measured.

Table 5 OC_DED bleaching of low-lignin pulps

	O-Stage					E-Stage		D-Stage					
	NaOH, %	Brightness	Kappa No.	Viscosity, cp	Yield, % wood	$KMnO_4$ No.	Viscosity, cp	ClO_2, %	Residual, %	Final pH	Brightness	PC No.	Viscosity, cp
MK-30	2.5	35.0	12.2	20.7	44.0	2.1	20.4	0.8	0.05	2.8	87.3	0.46	18.3
								1.2	0.19	2.8	88.7	0.46	17.9
								1.6	0.30	3.1	89.9	0.36	17.0
								2.0	0.40	3.2	89.9	0.31	16.9
MK-20	1.5	34.6	11.3	15.7	42.5	2.3	14.6	0.6	0.00	4.6	83.3	1.00	13.9
								0.8	0.04	4.2	87.5	0.61	14.2
								1.2	0.12	3.4	88.7	0.42	13.8
								1.6	0.26	3.7	89.2	0.47	14.1
MKA-30	3.0	39.8	8.5	18.3	44.7	1.8	17.9	0.8	0.08	3.2	87.7	0.37	16.4
								1.2	0.27	3.4	87.8	0.38	15.6
								1.6	0.35	3.6	88.5	0.31	15.1
								2.0	0.49	3.2	89.2	0.28	14.4
MKA2-30	1.7	34.2	10.4	18.9	45.1	1.9	17.2	0.8	0.00	4.8	85.2	0.84	16.4
								1.2	0.21	4.3	87.7	0.48	16.3
								1.6	0.38	4.4	88.8	0.45	15.2
MKA-20	2.5	40.6	6.9	13.5	42.4	1.3	13.5	0.6	0.00	4.2	86.6	0.51	13.2
								0.8	0.12	4.0	88.0	0.32	13.1
								1.2	0.24	3.7	88.7	0.37	12.3
								1.6	0.41	3.9	88.5	0.29	12.2
	1.5	34.5	8.8	14.8	42.8	1.8	13.2	0.8	0.00	4.5	86.2	0.77	12.9
								1.2	0.12	4.4	87.1	0.57	12.4
								1.6	0.40	4.2	88.3	0.49	11.7

[a]Conditions: Oxygen (O) 30 min, 110-120°C, 27% consistency, 100 psig O_2, 0.1% Mg^{++}, 2.2% NaOH.
Chlorination (C_D) 20% carryover of O-stage effluent, 45 min, 25°C, 3% consistency, % Cl_2 (incl. equiv. of ClO_2) = 0.25 x kappa, 15% replacement of Cl_2 with equiv. ClO_2.
Extraction (E) 5% carryover of E-stage effluent, 60 min, 60°C, 10% consistency, % NaOH = 0.55 x total equivalent Cl_2.
Chlorine Dioxide (D) 180 min, 70°C, 10% consistency; % NaOH = (0.4 or 0.5) x % ClO_2.

[b]Chemical charges and residuals based on o.d. oxygen-bleached pulp wt.

Table 6 Physical properties of unbleached and OC_DED bleached pulps[a,b]

Pulp Type	Unbleached: Viscosity, cp	Unbleached: Tear at 9 km Tensile B.L.	Unbleached: Tensile B.L. at 400 CSF, km	Unbleached: Maximum Zero-span B.L., km[c]	Bleached: Viscosity, cp	Bleached: Tear at 9 km Tensile B.L.	Bleached: Tensile B.L. at 400 CSF, km	Bleached: Maximum zero-span B.L., km[c]
CK	32.8	175	10.3	20.7	17.8 27.6[d]	155 150[d]	10.6 10.7[d]	20.4 20.2[d]
MK-30	32.8	180	10.4	19.8	19.0	160	10.4	20.0
MK-20	18.6	155	9.7	19.9	13.8	140	9.5	19.3
MKA-30	--[e]	--[e]	--[e]	--[e]	16.2	150	10.4	19.9
MKA-20	18.6	145 150[f]	10.4 10.1[f]	20.1 20.7[f]	12.9	145	9.7	18.8

[a]Bleaching conditions as in Table 5; the amount of ClO_2 used in the last stage was in each case the minimum amount required to reach a brightness of 87.5, as determined in the experiments of Table 5.

[b]The pulps were beaten in a PFI mill to 5 different freeness levels in the range 750-350 CSF.

[c]Zero-span tensile breaking length was measured at each beating interval; the value shown is the highest of those measured.

[d]Bleached in the CEDED sequence.

[e]Not determined.

[f]From duplicate PFI mill run.

Table 7 BOD production in bleaching conventional and low-lignin pulps

Pulp Type	Bleach Sequence	Individual Stage BOD_5[a], lb/ton O	C_D	E	D	E	D	Sum[b]	Combined[c]
CK	C_DEDED		12.6	7.5	19.3	2.2	1.7	43.2	n.d.[d]
	OC_DED	10.1	11.4	5.9	2.6			19.9	n.d.
MK-30	OC_DED	9.6	3.9	2.4	2.0			8.4	n.d.
MK-20	OC_DED	4.8	4.2	2.5	1.3			7.9	8.8
MKA-30	OC_DED	13.0	4.5	1.6	1.3			7.4	n.d.
MKA-20	OC_DED	10.7	3.5	1.9	1.0			6.4	7.8

[a]Five-day BOD in total effluent less carryover to succeeding stage (5% from C_D stage, 20% from others); perfect washing after last stage is assumed. Bleaching conditions as for Table 6.

[b]Sum of contributions from all stages except oxygen stage.

[c]From analysis of combined effluent from all stages except oxygen stage.

[d]n.d. = not determined.

Table 8 Color production in bleaching conventional and low-lignin pulps

Pulp Type	Bleach Sequence	Individual Stage Color[a], lb/ODT						Sum[b]	Combined[c]
		O	C_D	E	D	E	D		
CK	C_DEDED		113	291	7	4	1	415	n.d.[d]
	OC_DED	94	82	162	2			246	n.d.
MK-30	OC_DED	78	36	52	2			89	n.d.
MK-20	OC_DED	43	42	69	2			113	72
MKA-30	OC_DED	110	28	28	1			58	n.d.
MKA-20	OC_DED	71	24	30	2			56	26

[a]Color in total effluent less carryover to succeeding stage; perfect washing after last stage is assumed.
[b]Sum of contributions from all stages except oxygen stage.
[c]From analysis of combined effluent from all stages except oxygen stage.
[d]n.d. = not determined.

Table 9 Comparison of pulping/bleaching sequences

Cook Type	CK		MK-30	MK-20	MKA-30	MKA2-30	MKA-20	
Time at 173°C, min	90		80	75	70	210	90	
Eff. alkali, % on wood	16		19.2	21.1	17.5	18.2	20	
AQ, % on wood	0		0	0	0.3	0.1	0.2	
Sulfidity, %	25		39.9	36.6	36.1	40	38	
L/W ratio, cc/g	4		5	4.1	4	4.9	4	
Screened yield, % on wood	46.5		45.4	43.2	45.7	45.8	43.4	
Kappa no.	35.1		22.6	17.9	19.0	21.3	15.4	
Viscosity, cp	32.8		32.8	18.6	26.3	33.1	18.6	
Bleach sequence	C_DEDED	OC_DED	OC_DED	OC_DED	OC_DED	OC_DED	OC_DED	C_DED
NaOH in O-stage, %	--	2.2	2.5	1.5	3.0	1.7	2.5	--
% Cl_2	7.5	4.0	2.6	2.4	1.8	2.2	1.5	3.0
% NaOH, except O-stage	5.7	3.0	2.0	1.9	1.5	1.7	1.3	2.4
% ClO_2	1.7	1.5	1.0	1.0	0.8	1.3	0.9	1.4
Chemical cost[a], $/ODBT	44.62	29.42	18.41	17.93	48.20	31.42	37.64	47.34
Bleach effluent BOD, lb/ODT	43.2	19.9	8.4	7.9	7.4	n.d.	6.4	n.d.
Bleach effluent color, lb/ODT	415	246	89	113	58	n.d.	56	n.d.
Bleached pulp brightness	87.8	87.2	87.3	87.5	87.7	87.7	88.0	85.5
Bleached pulp viscosity, cp	27.6	19.2	19.0	13.8	16.2	16.3	12.9	15.9
Bleached pulp tear factor[b]	150	150	160	140	150	n.d.	140	155
Bleached pulp yield, % o.d. wood	43.2	43.5	43.3	41.6	44.0	43.8	42.1	42.1
Chemical cost, $/ODT wood	19.27	12.80	7.97	7.46	21.21	13.76	15.85	19.93
Pulp revenue, $/ODT wood	151.20	152.25	151.55	145.60	154.00	153.30	147.35	147.35
Pulp revenue less chemical cost, $/ODT wood	131.93	139.45	143.58	138.14	132.79	139.54	131.50	127.42

[a]Combined costs of bleaching chemicals and anthraquinone (excludes other pulping chemical costs); unit costs assumed as follows: Cl_2, $0.072/lb; NaOH $0.135/lb; ClO_2, $0.45/lb; anthraquinone, $2.50/lb. Cost of NaOH in O-stage not included. Bleached pulp valued at $350/ODT.

[b]At 9 km breaking length.

[c]n.d. = not determined.

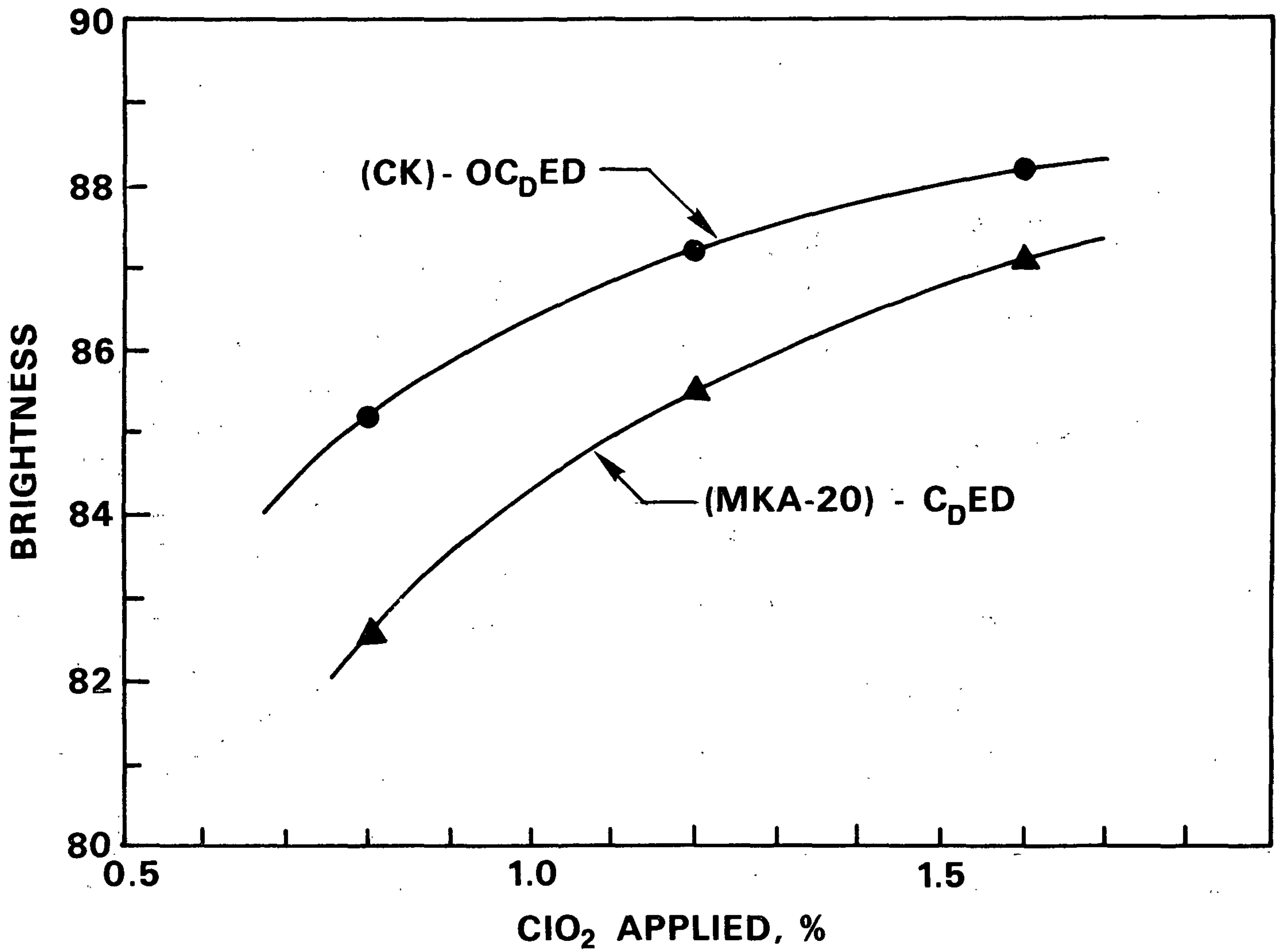

Fig. 1 Pulping to lower kappa number is an alternative to installing an oxygen stage.

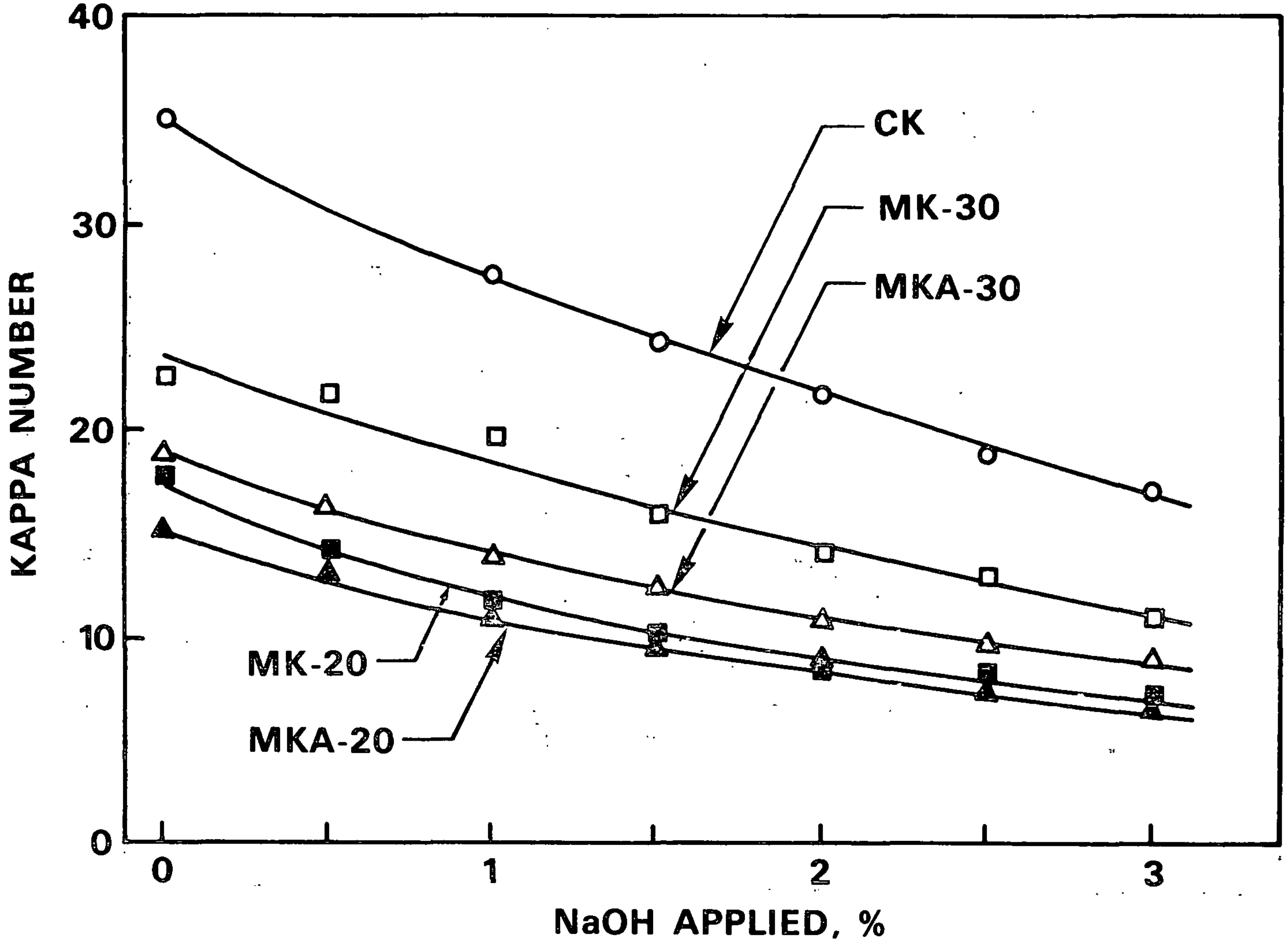

Fig. 2 Low-lignin pulps delignify normally in an oxygen stage. Conditions: 30 min, 110°C, 27% consistency, 100 psig O_2, 0.1% Mg^{++}.

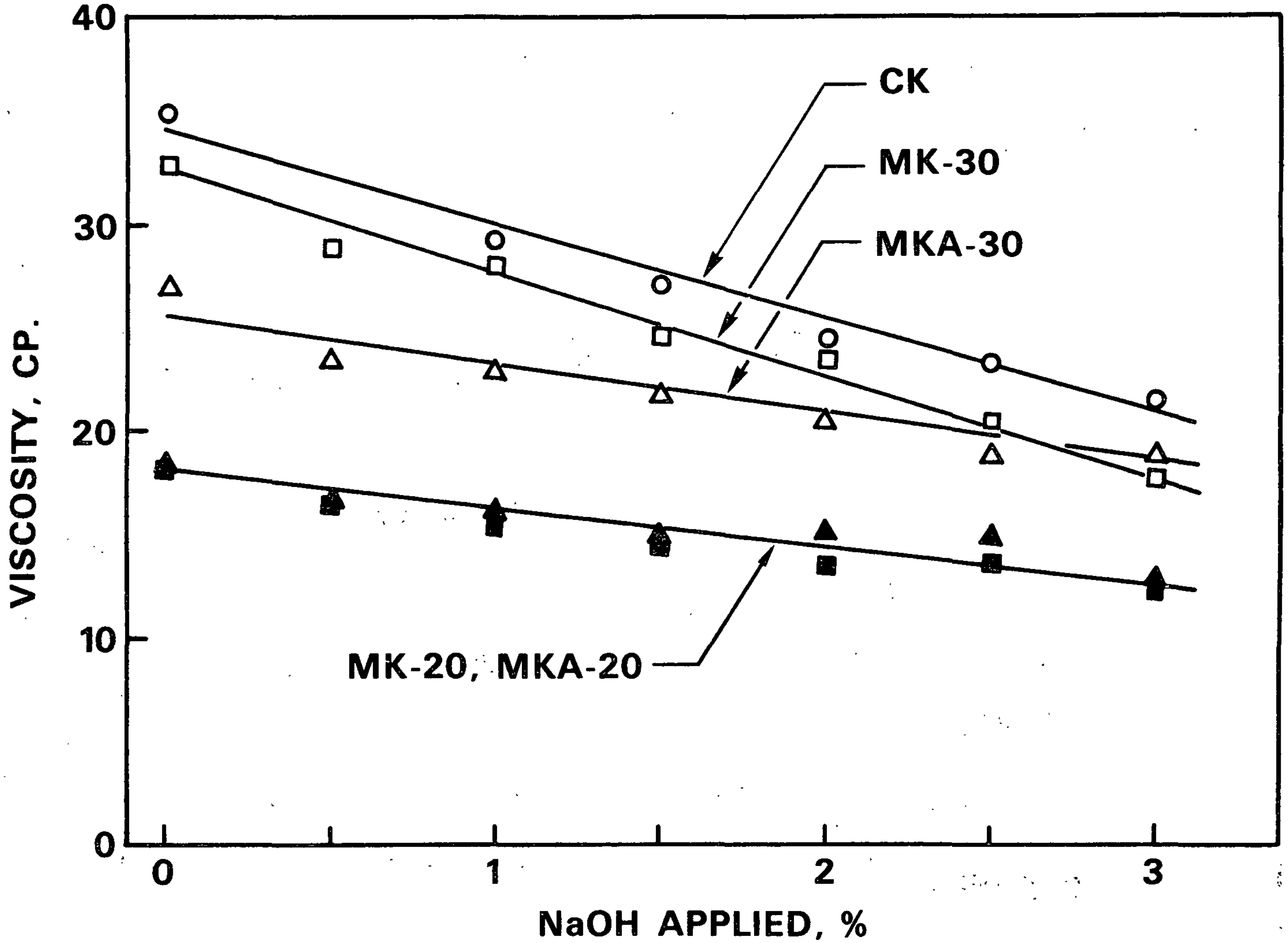

Fig. 3 The resistance of low-lignin pulps to viscosity loss in the oxygen stage depends on pulping conditions. In some cases low-lignin pulps are better than conventional kraft in this respect. Oxygen stage conditions as is Fig. 2.

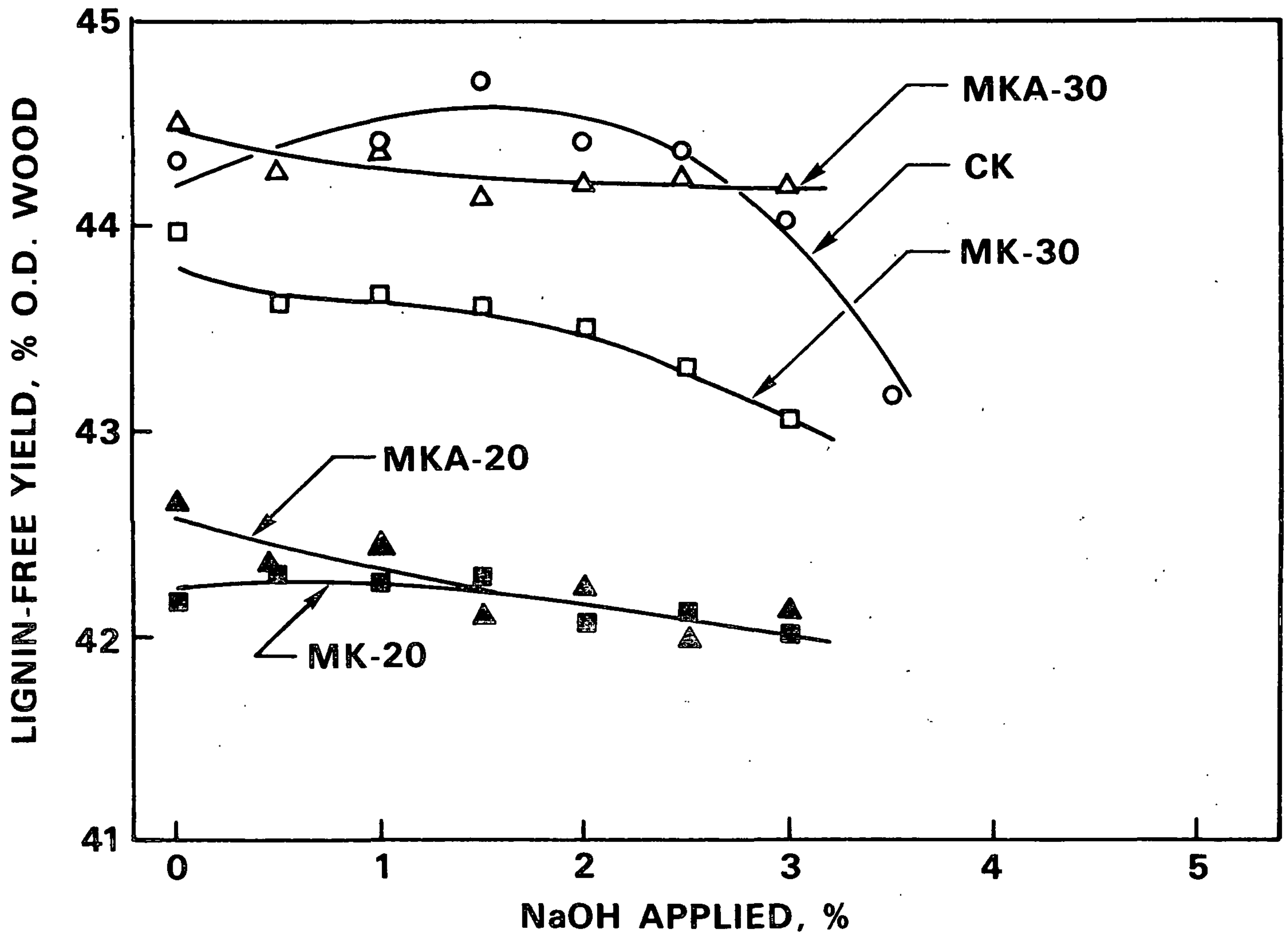

Fig. 4 Yield selectively in the oxygen stage depends on pulping conditions and is better for some of the low-lignin pulps than for conventional kraft. Oxygen stage conditions as in Fig. 2.

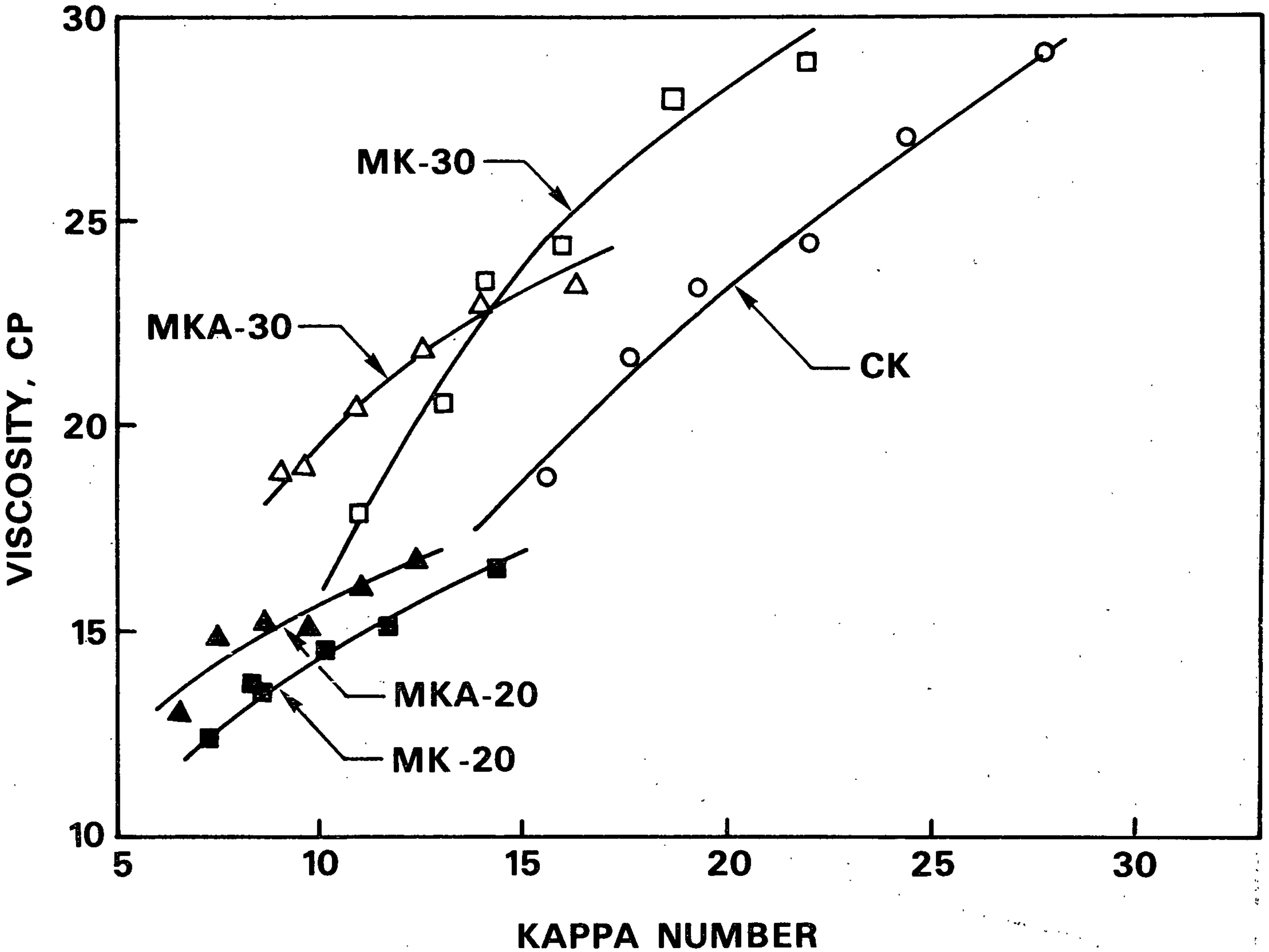

Fig. 5 At a given kappa number after the oxygen stage, low-lignin pulps have higher viscosities. Oxygen stage conditions as in Fig. 2.

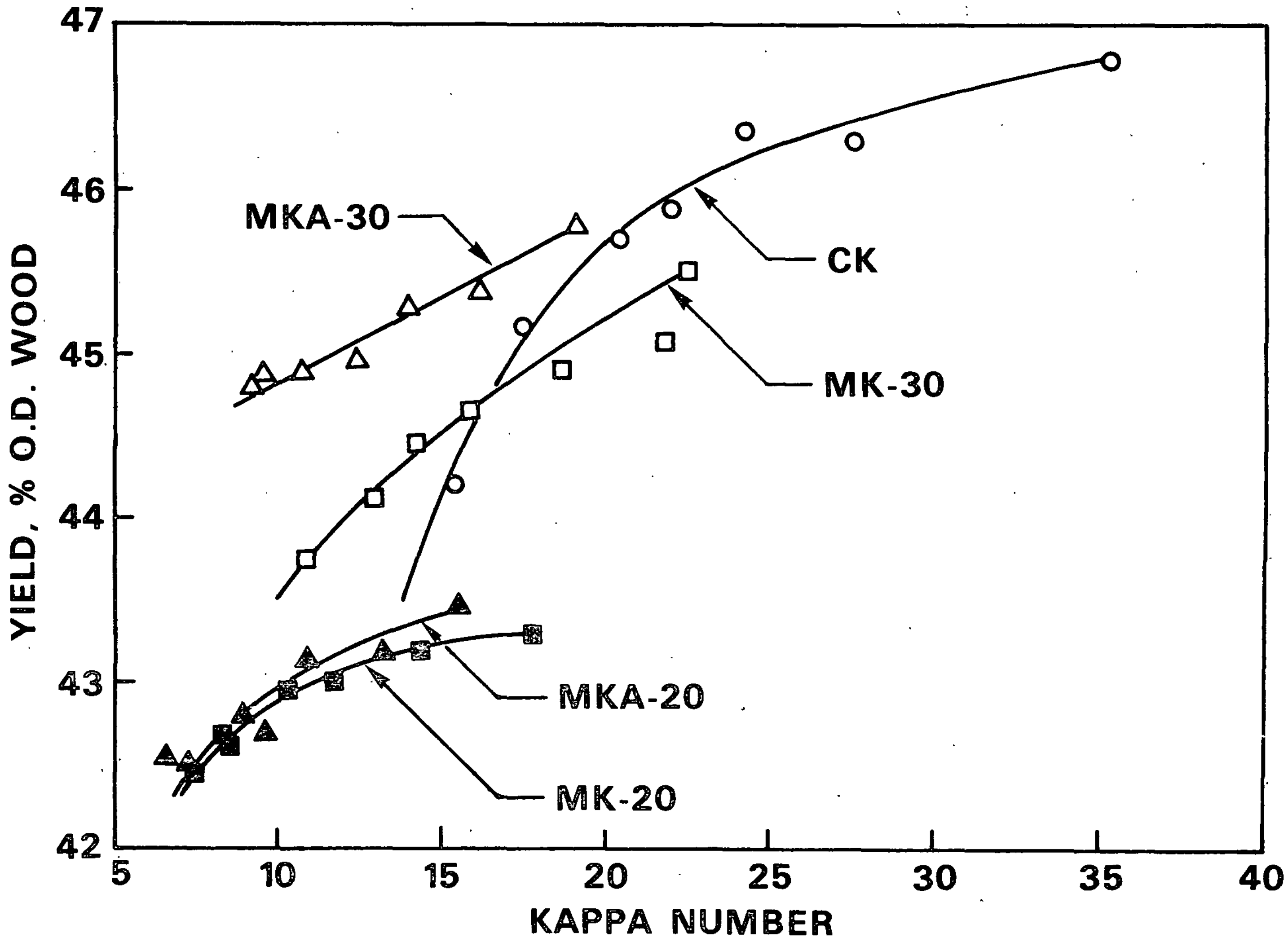

Fig. 6 After oxygen bleaching to low kappa number, low-lignin pulps have higher yields than conventional kraft.

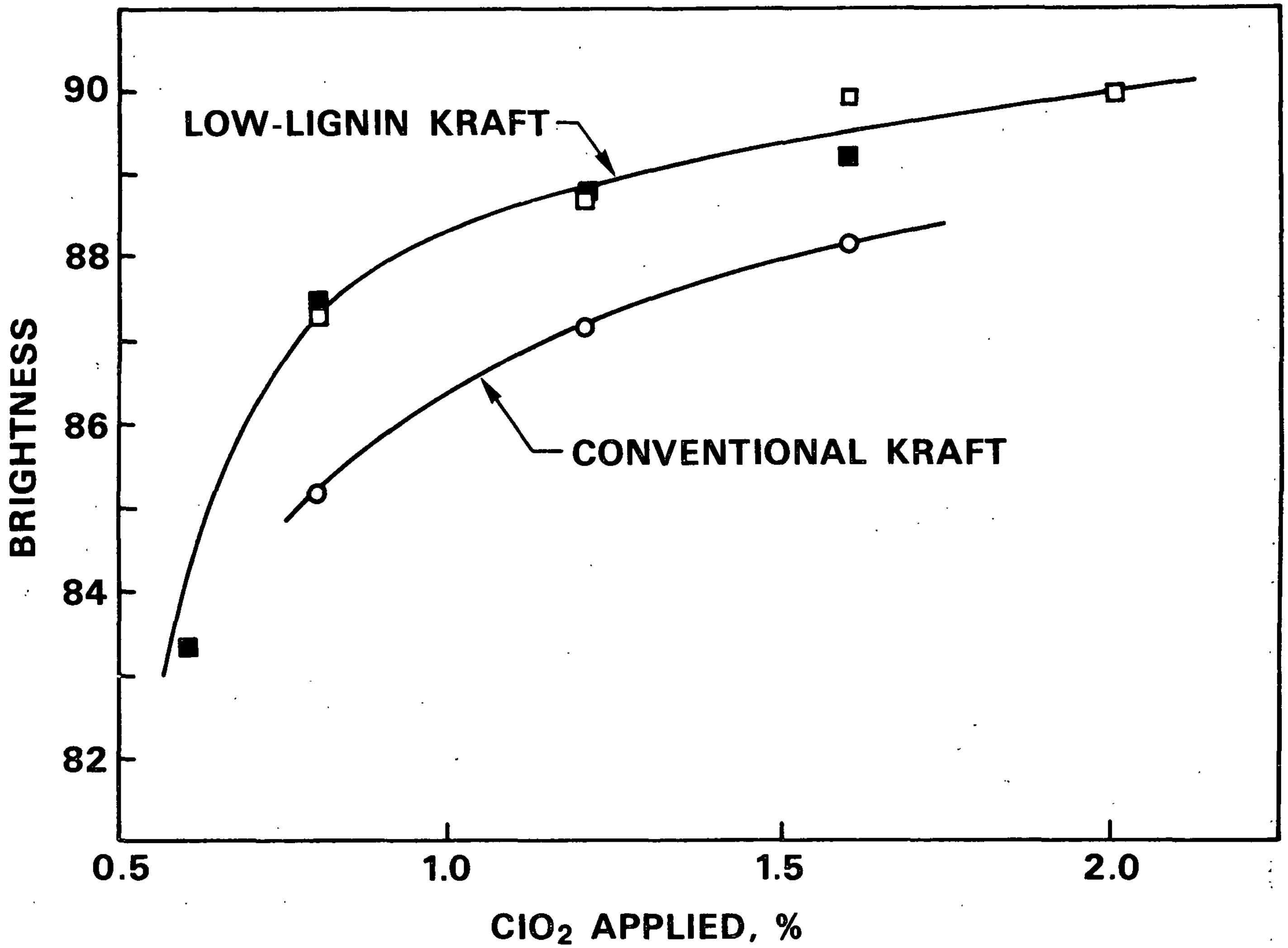

Fig. 7 Low-lignin kraft pulps can be bleached to higher brightness in the OC_DED sequence than conventional kraft.

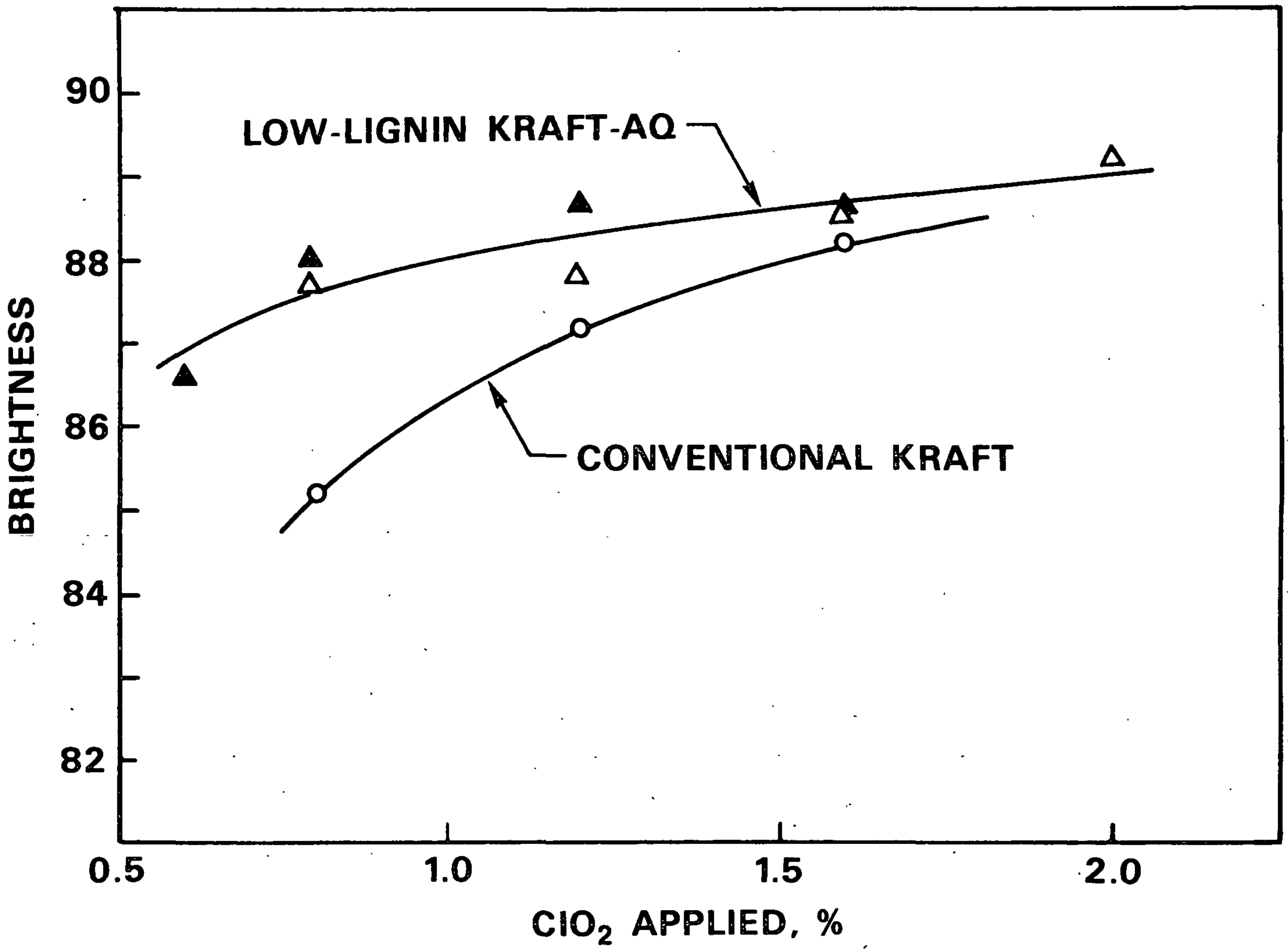

Fig. 8 Low-lignin kraft-AQ pulps are more readily bleached to high brightness in the OC_DED sequence than conventional kraft.