Mill experience in high-consistency ozone bleaching of southern pine pulp

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ABSTRACT: In September 1992, Union Camp began production on the world's first high-consistency ozone bleach plant at its mill in Franklin, VA. The four-stage OZ(EO)D bleach line has a daily production capacity of 1000 air-dry tons of kraft southern pine pulp. The expected performance of this bleach line has been discussed in earlier reports based on pilot and laboratory data. This report presents actual operating data from the line, with emphasis on effluent quality, pulp quality, operating conditions, and bleaching costs. Startup preparation, training, and startup problems are also discussed.

KEYWORDS: Bleach plants, costs, ecology, effluents, high consistency, kraft pulps, multistage process, operations, ozone bleaching, Pinus, pulp properties, quality, Virginia.

The Union Camp mill at Franklin, VA, has been operating the world's first high-consistency ozone bleach plant for 18 months. This article details many of the benefits provided thus far by the mill's new F bleach line.

Background

For many years, the Franklin mill used twin CEDED lines (A and B lines) to bleach an average of 700 air-dried (a.d.) tons per day of southern pine pulp. **Figure 1** is a schematic of the CEDED sequence used on the A and B lines. These lines provided reliable service for many years, but they had recently become environmentally and operationally obsolete.

After years of laboratory and pilot experience, Union Camp decided to replace the two aging CEDED lines with the first commercial bleach sequence containing a high-consistency ozone bleaching stage. The forces driving the project were the mill's need to lower water usage and effluent color, reduce BOD (biochemical oxygen demand), and abate generation of chlorinated organics. The low bleaching costs of the OZ(EO)D sequence added to its attractiveness. Nutt *et al.* provide more details on the motivation for installing the ozone-based bleach sequence *(1)*.

Franklin's F bleach line was designed to bleach as much as 1000 a.d. tons/day of conventional, batch-cooked, screened, pine brownstock of approximately kappa no. 27.5 (about kappa no. 30 after cooking, which drops with brownstock washing and screening prior to the bleach plant). The bleaching sequence consists of an oxygen (O) stage and an ozone (Z) stage, followed by an oxygen-augmented extraction (EO) stage and a chlorine dioxide (D) stage. The oxygen and ozone stages operate at high consistency. The stock from the oxygen stage passes through two wash presses before being split into two parallel Z stages, each with a capacity of 500 a.d. tons/day. Each ozone reactor is preceded by a displacement press that discharges the stock at high consistency (above 35%). A common Z-stage drum washer is used for both Z reactors, and the washer is followed by conventional EO and D stages with capacities of 1000 a.d. tons/day. **Figure 2** is a simple schematic of the system.

Ozone gas is generated on the roof of the bleach plant. The ozone is piped to the process for immediate use after generation. Also located

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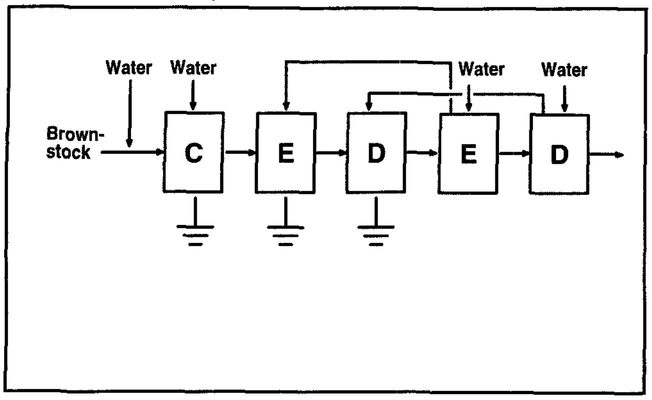
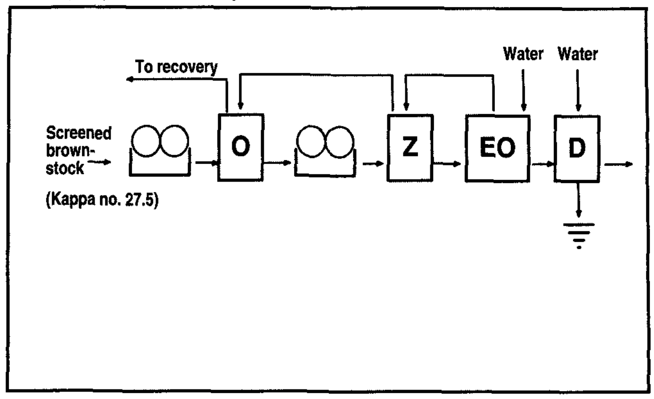
1. CEDED bleach sequence used in the old A and B lines



2. OZ(EO)D bleach sequence used in the new F bleach line



on the roof is a full gas recycle and purifying system that allows reuse of the spent ozone reactor gases with a controlled oxygen makeup.

A combination of fresh water and paper-mill white water is used for showers on the E and D stages. The D-stage filtrate is sewered because of its chloride content. The E-stage filtrate is cycled in a countercurrent fashion to the Z-stage showers. The Z stage supplies water to the post-oxygen washers, with full counter-current recycle to brownstock washing. Acid is applied to the Z-stage feedstock dilution flow and is recycled in a closed pressate loop. The small purge that is used in this acidification loop is still being optimized.

Training/startup

Startup of the F bleach line was very successful. Target-brightness pulp was being produced less than 48 hours after stock was brought to the first stage. This success was due in large part to a well-trained operating staff.

Management committed both the trainer and trainee resources to provide comprehensive, uniform training. One extra shift of operators was added for the entire 15-week training period. All training sessions were held during the day and on straight time, which spared the workers left on shift from having to work overtime. As a result, the operators were fresh for their training. They were also able to receive training in three complete week-long sessions, which added continuity.

The creation of a core training group enhanced the training continuity. A group of engineers, superintendents, operators, and assistant superintendents conceived, created, scheduled, and provided the training. This same group worked together from autumn 1991 through the end of training in late spring 1992. Each shift of operators received the same training, with the same emphasis, from the same trainers.

Possibly the biggest contributor to the successful startup was the creation of a bleach plant simulator. This real-time simulator used the graphics and control panels on the F bleach line's distributed control system (DCS). This gave the operators a realistic feel for starting and operating the bleach plant and allowed them to become familiar with DCS controls for the first time. The simulator was also invaluable in teaching interlocks to the operators. Each operator spent roughly 40 hours on the simulator. It is estimated that the simulator shortened the startup learning curve by three weeks.

Table I lists the significant dates for startup of the F line. Stock was first brought into the oxygen stage on August 17. An O(DC)(EO)D sequence was used for the first few weeks of startup. The DC stage was built as a cheap insurance policy to allow flexibility in making any necessary Z-stage modifications. Since storage capacity was already needed in front of the Z-stage washer, an insurance policy could be bought for the price of a DC mixer. This proved advantageous, since the Z-stage and ozone-generation equipment were still being commissioned in early August.

The first ozone-bleached pulp was produced on September 4 during a brief run to check out the Z-stage and ozone-generation equipment before the annual millwide shutdown over the Labor Day holidays. The

I. F-line startup, 1992

Aug. 1	O(DC)(EO)D line mechanically complete.
Aug. 17	Begin first production using O(DC)(EO)D mode. Ozone system still being commissioned.
Sept. 4	First trial use of ozone. Initial results looked excellent.
Sept. 6–15	Annual mill shutdown. F line not operated.
Sept. 19	F line converted to continuous use of ozone. Operation has been continuous since that time, although there have been some outages for various reasons.

II. Bleach plant effluent losses for kraft pulp (southern pine) at 83% GE brightness

	Predicted from lab or prior mill tests		Mill measurements
	CEDED	*OZ(EO)D*	*OZ(EO)D*
BOD_5, kg/a.d. metric ton	16	2	1.8
COD, kg/a.d. metric ton	65	6	5.6
Color, kg/a.d. metric ton	185	1.5	0.9
TOX, kg/a.d. metric ton	6.5	0.075	0.14
AOX, kg/a.d. metric ton	...	...	0.058
Chloroform (total), kg/a.d. metric ton	0.18	0.002	0.0017
Chlorophenols, ppb	...	...	ND*

*Not detected (<1.2–5 ppb); EPA Method 1653

III. Dioxin analysis for kraft pulp (southern pine) bleached in OZ(EO)D sequence—mill results

	TCDD		TCDF	
	Analysis	*Detection limit*	*Analysis*	*Detection limit*
Pulp, ppt	ND	0.1–0.5 ppt	ND	0.4 ppt
D-stage filtrate, ppq	ND	1.2–8 ppq	5.6 ppq (ND-12 ppq)	1–7 ppq

ND = not detected

run was very successful, and Z-stage results were close to expectations. Because of complications in pulp mill operations, the F line was late restarting after the shutdown. Full-time use of ozone began on September 19. Since that time, ozone use has been continuous except for several brief outages.

Early startup problems

Although the overall startup of the F bleach line was quite successful, it was not without its complications. Several problems were encountered in the months after startup. In December, corrosion in the Z-stage acid pressate loop caused a failure of the Z-stage feed press-roll deck. This corrosion was a result of improper metal selection for the low-pH environment and the buildup of certain components because of filtrate recycle. Unfortunately, the metal chosen for use in the bleach plant was different from that which had given good service in the pilot plant. The new material was chosen on the basis of corrosion literature, which indicated acceptable service for the expected environment. In January, after a short run using our backup DC stage, the press rolls were replaced with a different alloy. This alloy has worked well and shows no signs of corrosion.

Another complication of filtrate recycle was a scale buildup in the Z-stage equipment. Scale accumulated in the stock chests, heat exchanger, and presses around the Z stage. The problem was caused by a buildup of calcium in the recycled filtrate and by the pH changes between the different stages. Filtrate-handling strategies were modified to alleviate this problem, and no scale problems have been encountered since then.

Heat inputs to the Z stage were also underestimated, resulting in higher-than-expected ozone reactor temperatures and a consequent loss of efficiency. The Z stage was designed to operate at temperatures below 125°F. Strength loss can be excessive above this temperature. Modifications to the cooling system have brought the temperatures back into range.

In the conventional equipment, D-stage tuning has been troublesome, partly because of the large tower size. The D-stage tower was designed for 5 h retention at 1000 tons/day. However, the F line often runs only 500 tons/day during low bleached pine pulls, and the large upflow leg in the D stage has made tower management difficult. Control of residual ClO_2 was an early problem.

One last area requiring adjustment on startup was the ozone-generation system. The initial system required significant operator attention. Simplification of controls and automation of the system have made it easy to start and run remotely with less operator attention.

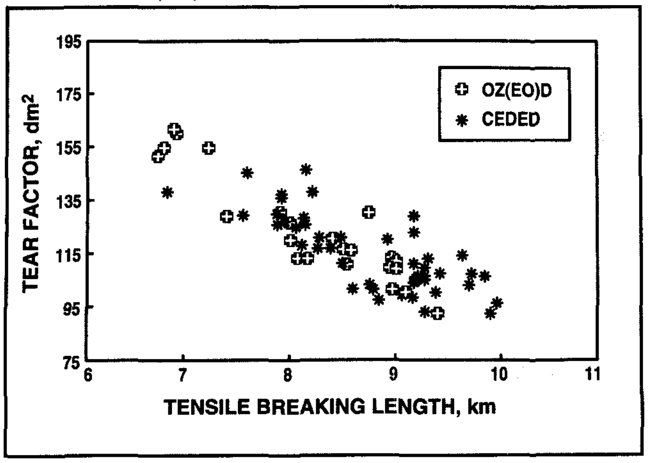
Environmental benefits

A large part of the motivation for installing the ozone bleach plant was the environmental benefits. Water use had been a concern at the mill for years because of the "hold and release" effluent system. The Franklin mill is situated on a small river and must hold effluent for eight months a year. Effluent is released during the winter, when river flow and oxygen levels are at their highest levels.

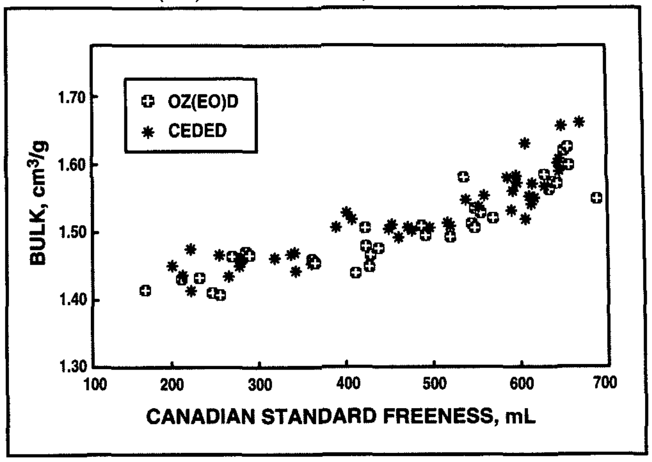
Minimizing color, BOD, and chlorinated organics in the effluent was also important. All of these key items have been greatly reduced by installing high-consistency ozone bleaching with full filtrate recycle. The importance of this full filtrate recycle cannot be overemphasized, for without it ozone bleaching becomes only a way to reduce chlorinated organics.

Since startup of the F line, BOD and COD (chemical oxygen demand) levels in the bleach plant have met expectations at 1.8 kg/a.d. metric ton

3. Tear vs. tensile for bleached kraft pulp (southern pine) after treatment in OZ(EO)D or CEDED sequences



4. Bulk vs. freeness for bleached kraft pulp (southern pine) after treatment in OZ(EO)D or CEDED sequences



and 5.6 kg/a.d. metric ton, respectively. F-line effluent color is actually below expected, at 0.9 kg/a.d. metric ton. **Table II** presents data about bleach-plant effluent *(2)*.

Table II also shows chlorinated organic levels measured in the F-line effluent. TOX (total organic halides) levels have been measured at 0.14 kg/a.d. metric ton. The TOX level measured thus far is above the expected value. This is probably due to the higher-than-anticipated ClO_2 application in the D stage. Efforts to reduce ClO_2 use are underway and are discussed later in this article. Despite the higher-than-expected numbers, the F line still has more than 20 times less TOX and AOX (adsorbable organic halides) than the old CEDED bleach lines.

Chloroform levels in the F line are extremely low, as seen in Table II. Total chloroform from pulp and effluent have been measured at 0.0017 kg/a.d. metric ton. No chlorophenols have been measured in F-line effluent at detection limits between 1.2 ppb and 5 ppb. A total of 28 different chlorophenols were tested for in the analysis.

No TCDD (tetrachlorodibenzo-*p*-dioxin) has been detected in the pulp or filtrate from the F line. TCDF (tetrachlorodibenzofuran) has been measured in the effluent at a low level of 5.6 ppq, but none has been found in the pulp. **Table III** provides details of dioxin analysis in pulp and filtrate from OZ(EO)D bleach sequence.

IV. Percent reduction in environmental emissions for OZ(EO)D bleaching of kraft pulp (southern pine) to 83% G.E. brightness

	OZ(EO)D vs. CEDED		OZ(EO)D vs. O(DC)ED
	Predicted	*Measured*[a]	*Measured*[b]
TOX	99	98	95
Chloroform	99	99+	99+
BOD_5	88	89	72
COD	91	91	75
Color	99+	99+	98
Volume of effluent	86	86	47

[a]Based on CEDED values in Table II
[b]Based on O(DC)ED data from Nutt *et al. (1)*

Emissions from the F line are much lower than from conventional bleach sequences. **Table IV** shows that the reductions range from 73% for TOX to more than 99% for chloroform when compared with the mill's old CEDED lines. Most of the reductions are in the 90% range. The reductions in emissions are still significant, even when compared with the previous state-of-the-art technology, an O(DC)ED sequence.

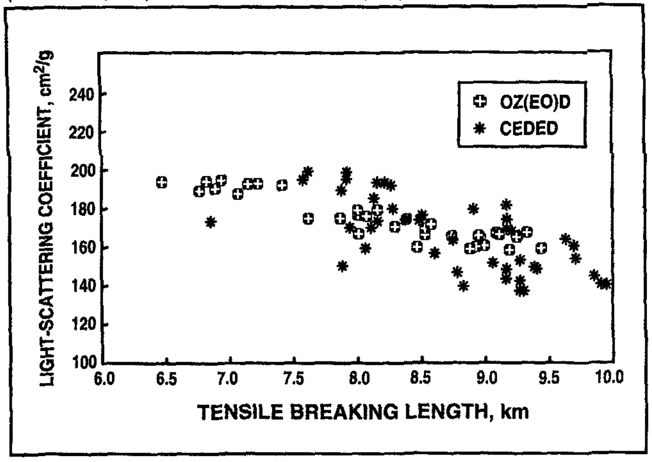
Effluent toxicity has also been exceptionally low. The toxicity of untreated effluent was tested with *Ceriodaphnia dubia*. The only adjustments to the effluent before testing were the standards for pH and residual oxidant. D-stage effluent toxicity, the only effluent, was very low, with an LC_{50}* of 70% *(3)*.

Bleached pulp properties

Concern over the preservation of pulp strength has been a major obstacle in the commercial implementation of ozone bleaching. Union Camp addressed these concerns through work in the laboratory and on a pilot scale. The results convinced management that it was possible to produce an ozone-bleached pulp that was equal in quality to conventionally bleached pulps. This has been the case with the F bleach line at the Franklin mill.

*LC_{50} is the concentration that is lethal to 50% of the test organisms.

5. Light-scattering coefficient vs. tensile for bleached kraft pulp (southern pine) after treatment in OZ(EO)D or CEDED sequences



6. Strength vs. viscosity for bleached kraft pulp (southern pine) after treatment in OZ(EO)D or CEDED sequences

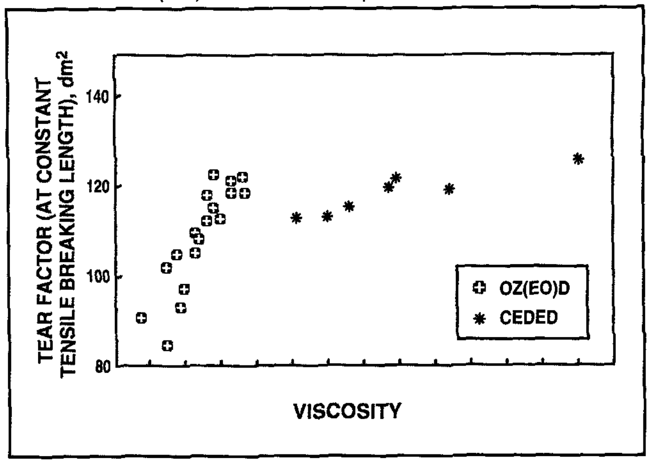


Figure 3 is a plot of the tear-tensile relationship for OZ(EO)D pulp from the F line and for CEDED pulp from the old bleach lines *(4)*. There is no statistical difference between the two data sets. From this comparison, one can conclude that the pulps are equal in strength as it would appear to an end user. As with any bleach sequence, the F line must be controlled to proper targets to produce quality pulp. These data show that when targets are met, the OZ(EO)D sequence can produce pulps as strong as any bleach sequence.

The mill's new OZ(EO)D line not only produces a pulp equal in strength to conventional pulps, but also one that is equivalent in other key pulp properties. **Figure** 4 shows a bulk-freeness comparison for pulps from the two sequences. Again there is no bias and no statistical difference between the two data sets. **Figure 5** shows the similarity between optical properties of pulps produced by the two sequences. There is no difference between the two plots of light-scattering-coefficient vs. tensile.

In summary, it is possible to produce an OZ(EO)D pulp that is equal in every significant way to a CEDED-bleached pulp. Two small differences are worth noting. One of these differences is a consistent indication that an OZ(EO)D pulp requires slightly less energy than a CEDED pulp to reach a common freeness. This expected change has not created any problems. There is also a shift in the viscosity–strength relationship when an OZ(EO)D pulp is compared with one from a chlorine-based sequence. This viscosity shift is meaningless except for knowing the target value that will provide a sufficiently strong bleached pulp. Figure 4 shows that pulp strength is equivalent for CEDED-bleached and OZ(EO)D-bleached pulps. The F line is simply controlled to a different viscosity target than the old CEDED lines. **Figure 6** shows the shift in the viscosity–strength relationship. The viscosity scale has been removed to protect the F-line operating targets.

Operation of the OZ(EO)D bleach line

As would be expected from any large new process, startup and operations on the F bleach line have not been trouble-free. However, the problems were not abnormal and, in fact, are considered exceptionally small for a new technology. Each of the four stages is generally meeting or exceeding its significant operating targets.

O stage

One key to the successful operation of a Z stage is an incoming pulp with a low kappa number. To meet this need, Union Camp installed a high-consistency oxygen stage instead of the more popular medium-consistency system. (The high-consistency oxygen stage at the Franklin mill is the fourth such stage operated by Union Camp.) The F-line O stage utilizes Union Camp's patented modified alkali distribution, which helps to preserve strength across the stage *(5)*. This O stage takes a conventional batch-cooked southern pine brownstock at kappa no. 27.5 and delignifies it to kappa no. 12.4. The 55% kappa reduction is well within the expected performance of the modified version of a high-consistency oxygen stage. The oxygen stage is capable of giving up to 60% delignification without significant strength loss.

Target selectivity is easily met in the O stage when in proper control. Typical viscosity drop across the stage is 5.7 cP (19.8 cP in, 14.1 cP out). This produces a selectivity (change in kappa number over change in viscosity) of 2.65. Target selectivity was expected to range between 2.3 and 2.7. Most medium-consistency oxygen systems are capable of producing similar selectivities, but with much lower delignification levels.

Pulp brightness exiting the O stage has been slightly below expected levels (36% vs. 39% GE brightness). The cause of this lower brightness is not fully understood and is still being investigated at the time of this writing. **Table V** provides operating data for the oxygen stage.

Z stage

Ozone-stage performance for the F bleach line has been especially encouraging. Since the first hours of startup, Z-stage performance has been at or very close to expected levels. All of the key equipment (reactors, presses, fluffers) has performed as planned, with no major equipment redesign needed. Equipment scale-up from the pilot plant was exceptionally accurate.

The Z stage operates at a pH of 2.0–2.5. A displacement press increases the pulp consistency to over 35%. This high-consistency pulp is then fluffed in a high-efficiency fluffer and conveyed via a pressure-sealing device into the ozone reactor. Proper control of these feed targets is critical in ensuring target strength and brightness in the Z-stage product. The Z reactor operates at low pressure, typically below 1 psig, which provides many safety benefits. (Ozone safety is discussed later in this work.) Ozone enters the Z reactor at the pulp discharge and flows countercurrent to a separation device at the pulp feed.

A slightly higher ozone charge has been added to the Z stage than was originally planned. This is mainly due to the lower-than-expected O-stage outlet brightness. Depending on incoming pulp conditions, the F-line ozone application ranges between 12.5 lb/a.d. ton and 15 lb/a.d. ton. Utilization of the applied ozone has been very high. Ozone consumption has been 95%, indicating effective gas–pulp mixing in the ozone reactor. This thorough pulp mixing also contributes to the uniformity of the Z-stage pulp, which has been exceptional since startup.

V. Performance of high-consistency oxygen stage in OZ(EO)D bleach sequence for kraft pulp (southern pine)

	Kappa no. In	Kappa no. Out	Delignification, %	Viscosity, cP In	Viscosity, cP Out	Selectivity, Δkappa/ Δviscosity	Outgoing brightness,* % GE
Target	25.5–28.5	11.7–12.4	54–56	20+	14+	2.3–2.7	39
Actual	27.5	12.4	55	19.8	14.1	2.65	36

*Brightness of feed to Z stage

VI. Performance of high-consistency ozone stage in OZ(EO)D bleach sequence for kraft pulp (southern pine)

	Ozone application Applied, lb/a.d. ton	Ozone application Consumed, %	Brightness, % GE In	Brightness, % GE Out*	Viscosity, cP In	Viscosity, cP Out	Selectivity, Δbrightness/ Δviscosity
Target	13	90–95	39	53	14+	10+	3.5
Actual	14.5	95	36	51	14.1	10.3	3.9

*Brightness of feed to ozone washer

VII. Typical performance of ozone generation and ozone gas recycle systems

O_3 conc., %	Power consumption,[a] kW·h/lb O_3	O_2 conc., %	O_2 makeup, lb O_2/lb O_3 Target	O_2 makeup, lb O_2/lb O_3 Actual	Typical operator attention, h/shift
6	6.1	90–92	2.3	2.9	<1

	Gas recycle composition after cleanup[b] O_2, %	CO_2, %	N_2, %	CO, ppm	HC, ppm
Predicted	86.0	9.56	4.2	3.7	<10
Actual	87.8	9.44	...	<5	<10

[a]Includes power of gas recycle system, O_3 generator power, and power for cooling needs (chilled water and cooling tower).
[b]After makeup O_2 is added.

Bleaching uniformity has been a concern of many who have studied ozone bleaching. Because of the rapid reaction between pulp and ozone, inadequate mixing in a high-consistency reactor can cause unevenly bleached pulp. Indeed, this was a problem in the original ozone reactor design in our pilot plant. However, extensive developmental work led to the design of a new type of reactor that eliminates the nonuniformity *(6)*. The ozone reactor installed at the Franklin mill has consistently produced a uniformly bleached pulp.

As a result of the extra ozone application, the brightness increase across the Z stage is higher than planned. The typical Z-stage outlet brightness of 51% GE gives a brightness increase of 15 points vs. the target of 14 points. Viscosity drop across the stage has been low. Typical viscosities are 14.1 cP into the stage and 10.3 cP for the outlet pulp.

VIII. Combined performance of EO and D stages in OZ(EO)D bleach sequence for kraft pulp (southern pine)

	Brightness, % GE			*Viscosity, cP*		
	In	*Out*	*Increase*	*In*	*Out*	*Decrease*
Target	57	83	26	10+	10+	0.5
Actual	55	84	29	10.3	9.6	0.7

IX. Reduction in bleach chemical costs for OZ(EO)D sequence vs. costs for CEDED sequence

	Cost reduction, %
Typical	26
Optimized	35

This gives a selectivity of 3.9 across the stage when expressed as change in brightness over change in viscosity. The target selectivity was only 3.5. Ozone-stage optimization still continues. It is expected that selectivity will be further improved and that ozone application will be reduced. **Table VI** provides operating information for the ozone stage.

Ozone generation

The ozone-generation system has met expectations. The initial startup was vexing because of an overly complicated control system and cumbersome interlocking. Since the system has been simplified and automated, however, it has performed well with minimal operator attention required. The generators have produced a wide range of ozone concentrations, but the typical target is 6%. Power consumption in the combined gas-generation/recycle system has been lower than expected because of very efficient ozone generation. The total system uses 6.1 kW·h per pound of ozone produced. **Table VII** provides data about the performance of the ozone-generation/recycle system.

The oxygen concentration in the feed gas to the ozone generators typically runs around 88–90%. This concentration is slightly higher than originally planned. The elevated oxygen concentration is reflected in the oxygen makeup flow of 2.9 lb O_2/lb O_3, which is higher than the expected makeup rate of 2.3 lb O_2/lb O_3. There is no process reason for the higher oxygen levels in the generator feed gas. Optimization of the control system should remedy the problem. With proper attention, the oxygen makeup is expected to be very close to target.

Other gas modeling based on pilot experience has been very accurate. Table VII compares predicted ozone-generator feed-gas composition with the actual measured values *(4)*. CO_2 is generated in the bleaching reaction and is the main contaminant in the gas recycle stream. At present, the mill uses liquid oxygen for makeup. Gas composition would obviously change with different makeup oxygen. With the accurate model that has been developed by Union Camp R&D, it is possible to accurately predict the impact of any changes in the gas recycle loop.

EO and D stages

The F-line EO and D stages have shown mixed results. In terms of brightening capability, the stages have exceeded expectations. Under typical operations, a brightness increase of 29 points is achieved. Even larger increases can be obtained if the line is pushed. Viscosity loss across the last two F-line stages has been slightly higher than originally targeted. This drop of 0.5–1.0 cP is consistent with the lower incoming brightness and the resulting higher ClO_2 dosage being used, compared with target. **Table VIII** provides data about the combined performance of the EO and D stages.

The higher ClO_2 use has been the downside of the conventional equipment. Optimization of the D stage has been difficult because of the large upflow leg and tower and the large turndown ratio of the line. Recent D-stage results have been encouraging, however, with a one-third reduction in chemical dosage.

Operating costs

The F bleach line has much lower bleaching costs than the old CEDED lines. The OZ(EO)D sequence thus far has produced a 26% savings in bleach chemical costs compared with the baseline CEDED sequence. The OZ(EO)D chemical use is not yet optimized and has decreased continuously since startup. The most recent operating data show a 35% savings, as seen in **Table IX**.

With the exception of acid use, Z-stage chemical consumption is on target. Ozone use has been at or close to target since startup. Acid use in the ozone stage is going to be higher than original projections because of the effects of filtrate recycle. Original projections for acid use were 1.25% on brownstock. Actual figures will be close to 2.5%. Chelant use has been at expected levels.

There is room for improvement in oxygen makeup to the ozone generators. Oxygen usage is expected to decrease to target once control is optimized.

The largest remaining area of emphasis in chemical optimization on the F line is the D stage. Optimization of the D stage has been difficult because of the large retention time built into the D tower and the large line turndown, which ranges as low as 400 tons/day. Dosages are expected to be close to target once full control is implemented. Recent operating data reinforce this expectation.

Ozone safety

Safe handling of ozone has been a major emphasis during the design, training, startup, and operation of the F bleach line. Since this is one of the first commercial ozone installations in the pulp and paper industry, Union Camp gave extra detail to ozone safety. Ozone toxicity is rated identical to that of ClO_2, as measured by OSHA limits (0.1 ppm PEL, 10.0 ppm IDLH). On the positive side, humans can detect ozone odor at levels well below the PEL. Based on four years of pilot experience in the safe handling of ozone and sound safety engineering practices, Union Camp designed a safe ozone bleach line. The F line has operated for almost a year with no harmful ozone exposures.

There are several keys to this safety success. One is the use of continuous ambient ozone monitors on each floor of the bleach plant. These monitors have served as continuous sentries to aid in the early detection of leaks. Another safe practice is the routing of all ozone relief vents to an active scrubber system. Special attention was also given to gas-tight equipment design, including the ozone reactor shaft seals and expansion joints.

The most important safety feature of the high-consistency ozone system is the low-pressure ozone reactor. The low reactor pressure (<1 psig) not only minimizes the likelihood of a leak but also minimizes the severity of any leak that occurs. A low-pressure system also adds to millwide and community safety by minimizing the total mass of ozone contained in the process at any one time.

Conclusions

Operating data from the first commercial application of high-consistency ozone bleaching demonstrate that:

- The OZ(EO)D bleach sequence produces a pulp equal in strength to that bleached in conventional chlorine-based sequences.
- Effluent from the OZ(EO)D bleach sequence is superior to effluent from any other bleach sequence available today.
- Bleaching costs of the OZ(EO)D sequence are significantly below those of conventional chlorine-based sequences. T

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