Optimizing the control of a batch digester house with an integrated distributed control system

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The control system maximizes digester production, minimizes energy and chemical costs, and optimizes pulp quality. With better control of delignification, the mill was able to increase pulp yield.

Control of operations in a batch digester house can be optimized through the use of an integrated distributed control system (DCS). This article describes the system in place at the Hopewell mill's digester house.

Hopewell's digester house

The digester house includes 12 directly steamed, 3000-ft^3 vessels loaded sequentially via multiple conveyor belts and liquor measuring tanks. Daily pulp production typically exceeds 1030 tons. The digester house is large enough to accommodate expansion to 14 digesters, as seen in the DCS video diagram of the house layout in **Fig. 1**.

Each digester is instrumented with steam flow, upper and lower temperatures, pressure, steam-valve position, relief-valve position, and an integrated interlock system for the cap, liquor fill, and blow valves. The system is charged, cooked, and blown automatically by computer control.

Three chip silos feed a transfer belt that loads the chips into one of two bins. A loading belt transfers chips from the bins to the digester-house operating floor. The loading belt is equipped with a device to measure wet packing density, a magnet for removing tramp metal, and a weightometer for measuring the total wet-chip charge to each digester. A belt tripper and screw mechanism diverts chips to either the east or the west side of the house. The tripper position and the screw rotation determine which digester will be loaded. A printout of the DCS video frame for chip charging is shown in **Fig. 2**.

The mill uses a fixed-sample-volume device coupled with load cells to measure the effective packing density of the chips. This system collects approximately 1000 lb of wet chips in a 25-ft^3 vessel mounted on load cells. During each chip charge, the measuring vessel is filled, weighed, and dumped. This density is used to calculate chip moisture and, subsequently, the required amount of chemicals.

Digester utilization is maximized by adding chips at the fastest rate possible. A chip pad is added to reduce vaporization of liquor as it enters the digester. Without a chip pad, the vapor leaving the digester impedes the flow of chips and can cause plugging. Even with the chip pad, it is necessary to interrupt the flow of chips to prevent plugging when the liquor valve initially opens.

Each digester is filled to its maximum capacity. A nuclear sensor indicates high chip level, causing the chip feed to stop and the belts to continue until the chips are clear. Each digester is thereby assured of a full chip charge. An operator-adjustable target for the maximum permissible wet weight is provided as a safeguard in case the nuclear sensor fails.

The weightometer mounted on the loading belt provides signals for both rate and integrated weight. A reasonably accurate measurement of the actual charge weight and calculated chip moisture is available for recomputing the correct charge of effective alkali (EA).

Two alternative loading strategies are possible: (a) Charge the digesters in a fixed sequence, or (b) charge the digester that has been idle for the longest time. Charging the digester with the longest idle time initially would appear to be the favored strategy. However, at Hopewell, the tripper travel time is the limiting factor. Immediately after the belt clears, the tripper is automatically positioned to the next digester in the charging sequence. The operator can enter the sequence through an interactive video frame.

Two blow tanks provide the volume required to support the production rate. The two blow lines (one for the west and one for the east side of the house) are interconnected via a crossover valve, allowing pulp from one side of the house to be blown into the blow tank normally used for the other side. The general arrangement of the blow tanks is shown in Fig. 1.

Motivation for installing a new system

Maintenance

Initial installation. A first-generation computer control system was installed in 1974. This system controlled charging, filling, *H*-factor, and blowing. It also had the

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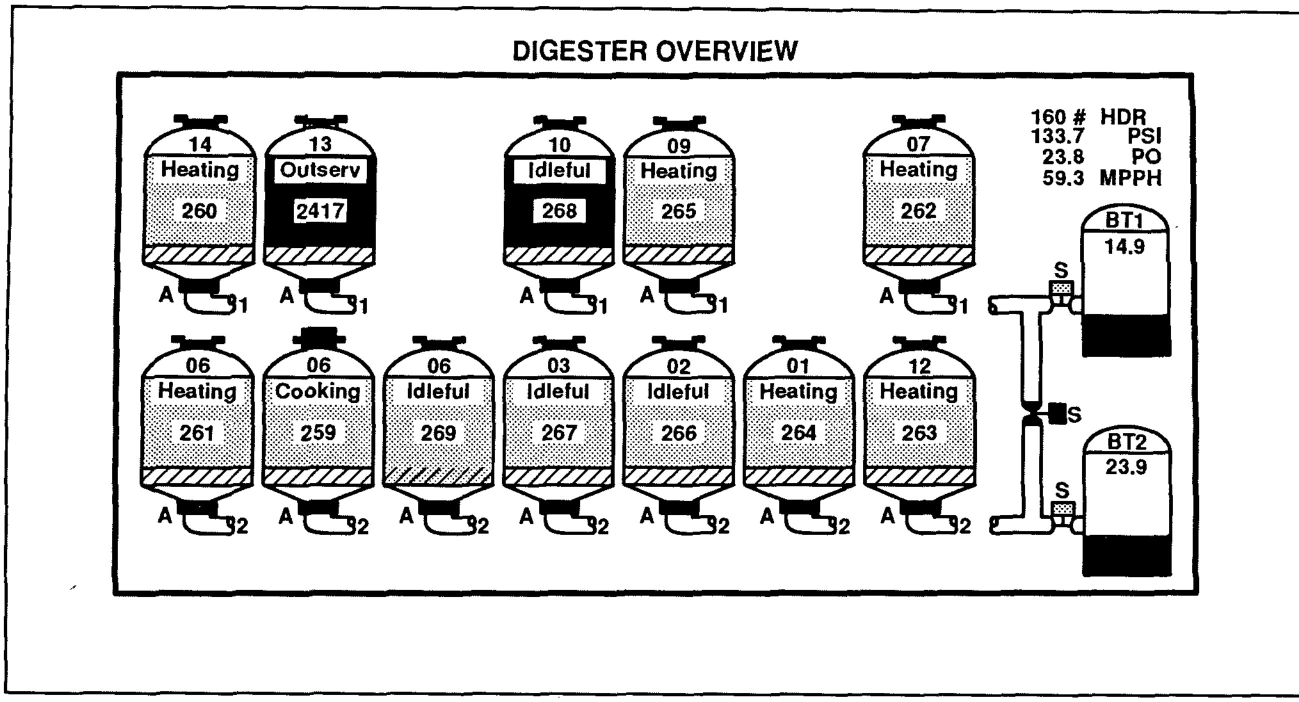
1. Video frame depicting layout of the Hopewell batch digester house



ability to "bias" the targeted chemical-to-wood ratio to accommodate the individual cooking characteristics of each digester.

Obsolete computer hardware. The input/output hardware and other components for the old computer system were becoming increasingly difficult to obtain. As corrosion deteriorated the hardware, frequent maintenance was becoming a necessity.

Obsolete software. The software was originally written specifically for the Hopewell mill in a vendor-specific process-control language. Nearly all available memory was used. Software changes had to be made with great care to ensure that they did not affect other portions of the program and that the proposed changes did not exceed the system's memory capacity. The mill decided to replace the system with an expandable new-generation system, thus eliminating the problem of obsolete software.

Anticipated benefits

Less variation in intra-cook kappa number. The delignification rate within a batch digester is not uniform throughout the vessel. Variations in chemical concentration vertically throughout the digester cause the delignification rate to vary vertically. As a result, the pulp discharged from most batch digesters suffers from intra-cook kappa number variations. Mill management sought to eliminate the nonuniform distribution of chemicals by installing an optimizing control system that added black and white liquor in proportion to the chip filling rate.

Constant chemical-to-wood ratio. The overall rate of delignification is a function of the EA-to-wood and the liquor-to-wood ratios. The charge of EA depends on the accuracy of four measured variables: white-liquor flow, wood mass rate, wood moisture, and white-liquor EA strength. The liquor-to-wood ratio depends on the accuracy of the black liquor flow, the wood mass rate, and the wood moisture measurement. Variation in any of these variables significantly affects the resulting liquor-to-wood ratio. By more accurately charging wood, chemicals, and black liquor, mill management expected to reduce kappa number variations. Using an online EA sensor, the mill would be able to compensate for variations in EA strength in the black and white liquors.

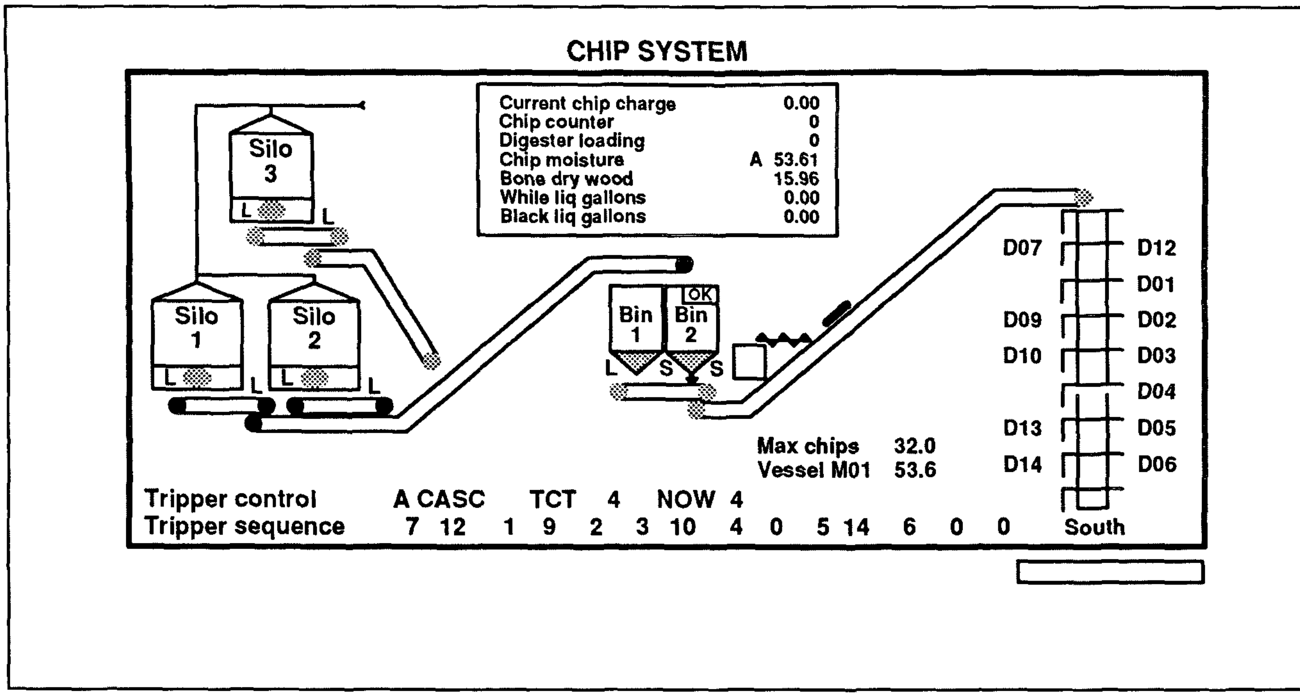
Less variation in white-liquor strength. White-liquor strength variations can cause significant variation in kappa number. The basic relationship between variation in kappa number and variation in chemical concentration within the digester is reflected through Chari's model (*1*).

The sensitivity equations are dependent on both the volumes of white and black liquor and the EA concentration in each. For example, if the white-liquor strength changes from 80 g/L to 84 g/L, the kappa number will change from 75 to 73.6, i.e., a 5% change in white-liquor strength leads to a 2% change in kappa number. This level of variation is not uncommon in typical pulp mills in the Southeast. If white-liquor strength is not tightly controlled, kappa number can swing at least ±1.5 units, even with constant chips, liquor, and *H*-factor.

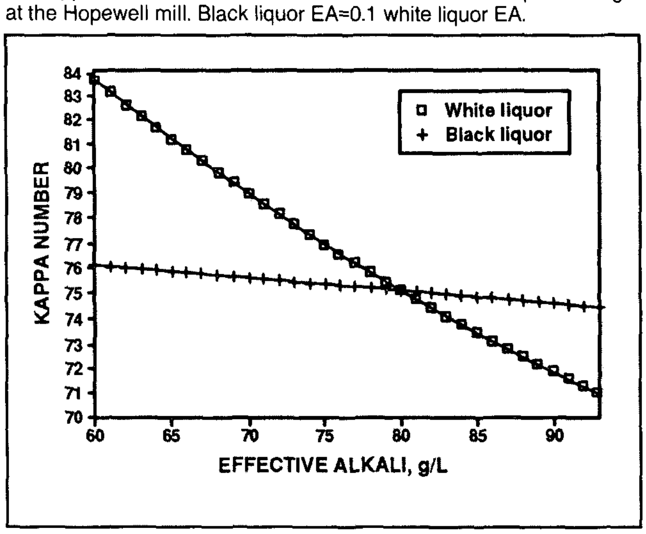
Some mills carry enough EA in the black liquor to influence chip delignification. The Hopewell mill wanted to be able to measure the black liquor strength and use that information when calculating the achieved chemical-to-wood ratio. **Figure 3** is a plot of the expected kappa number vs. the EA strength in the black and white liquors for the conditions at the mill.

Variation in white-liquor strength is primarily due to changes in the causticizing process. Slaker temperature, causticizer short circuiting, and lime quality can cause short-term swings in white-liquor strength. Finally, variation in green-liquor strength (caused by reduction efficiencies in the recovery boiler) also influences the concentration of white liquor. The mill wanted to be able

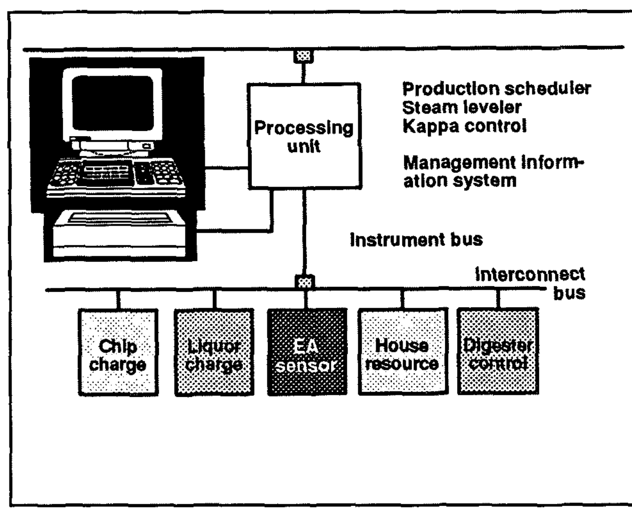
2. Video frame depicting the chip loading system



3. Kappa number as a function of black- and white-liquor strength at the Hopewell mill. Black liquor EA=0.1 white liquor EA.



4. Architecture of control hardware



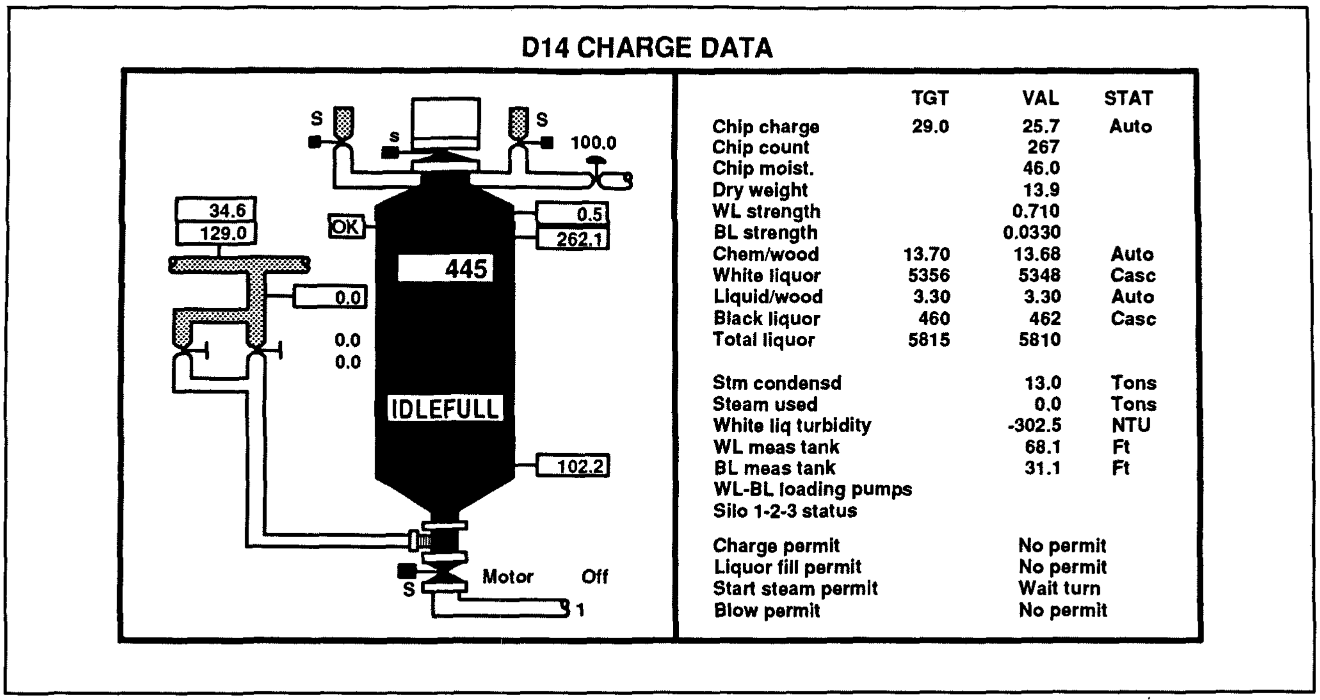
to measure and compensate for these variations and thus reduce kappa number variation.

Heat-time optimization. The time required to reach cook temperature can be extended whenever the specified production rate allows for idle time. High-temperature impregnation appears to produce a pulp of greater uniformity, since the alkali penetration is more efficient at higher temperatures. Increasing the heating time by several minutes would, for example, increase the time of impregnation at temperatures above 250°F. Maximization of the heating time is thus an important aspect in obtaining better pulp quality. The mill wanted a system that could optimize the heat-time phase of the cooking cycle.

Energy reduction. If idle time is available, cooking temperature can be reduced by extending the cooking time. This lowers the amount of steam required to reach cooking temperature, thus reducing the overall energy cost per ton of pulp. The mill wanted a system that was flexible enough to accommodate such energy-reduction strategies.

Increased production rate. The overall house production rates can be increased by increasing the efficiency of chip packing. This is a further benefit obtained by adding liquor-modulation valves to the house. Thus not only does the liquor packing increase the weight of chips per charge, it also helps control the vertical chemical concentration in the digester. The mill wanted to increase the production of pulp to accommodate improvements in paper machine operations.

5. Video frame depicting digester charge data



Control system

Strategy

Basic control functions. A method of optimizing large systems was introduced by Williams in the early 1950s (*2*). Williams broke the system down into the smallest subsystems possible and optimized the performance of each subsystem independently. The performance of the subsystem was then transmitted to the overall optimizing system, which simply adjusted the objective functions of the subsystems to obtain maximum performance of the overall system. This "hierarchical control" has been used extensively over the past 40 years. Early computer-controlled batch digesters (*3*) used a centralized approach, and only recently have the control functions been relegated to the lower-level functions (*4*).

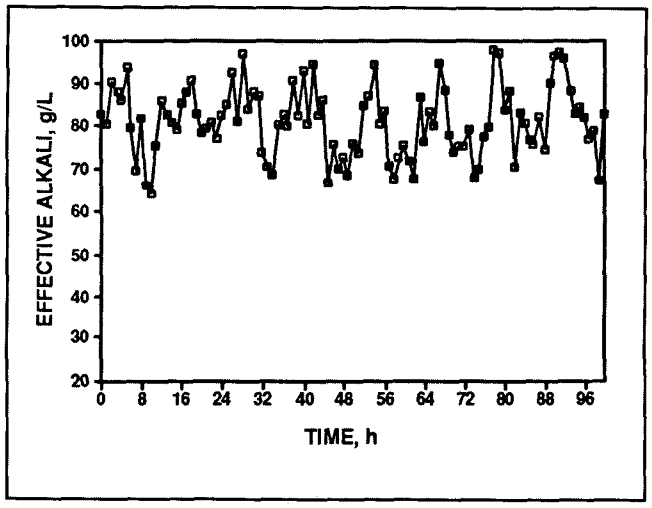
The batch digester control-system architecture uses hierarchical control. The basic subsystem is the individual batch vessel. Other subsystems are the chip-loading, liquor-filling, and blow-tank functions. Optimization is achieved by telling each subsystem to optimize its performance function independently. The digesters have *no* knowledge of each other.

Each digester is issued targets for pressure, temperature, heat time, cook time, and kappa number. The controllers for each of these functions operate independently of other digesters; however, within each digester subsystem, they operate in concert.

Chip-loading and liquor-filling functions are also performed independently. The objective function for the chip-loading subsystem is to minimize the time required to fill a digester. A similar objective function is set for the liquor-filling subsystem, but with the constraint that the chemical-to-wood and liquor-to-wood targets be met.

Isolation of functions. The overall hardware architecture is shown in **Fig. 4**. The subsystem functions are

6. Typical EA variations in the white liquor



performed in independent hardware modules, with the optimization functions performed in the "area" computer. Since subsystem control functions are performed in distributed board-level hardware, failure of a given board affects only that function.

One of the more difficult design criteria in any process-control system is the transfer mechanism between manual and automatic control. This is particularly important during the startup phase of the project. In the case of batch digesters, the transfer of discrete devices from manual to automatic also must be performed without changing the state of the device.

DCS implementations of bumpless and balanceless transfers require interfaces to manual transfer stations for both continuous and discrete devices. This was accomplished by providing momentary outputs to all safety-related discrete devices. Manual transfer stations are not required for the continuous-control devices because of the high reliability of the board-level controls and the ability of the operators to manipulate the output directly through an independent video console.

Communications. The mill has a local area network (LAN) that connects the batch digester with the power/recovery boiler system. Additional systems will be connected to the network in the future.

Each major unit operation such as the batch or the recovery boiler collects process information via a serial link to the distributed processors. This link collects data from the individual boards at rates up to once each second. Typically, the area computer will request data every two or three seconds. New optimization instructions are sent to the boards on a demand basis. Typically, the digester control boards receive data every 5 s for continuous data and every 1 s for discrete-control information.

The individual boards communicate with each other on a high-speed serial bus. This allows the various functions to communicate with each other without support from the area computer.

Digester control

The digester controls include: heating, cooking, blowing, relieving, turnover, shakeup, and blow-back controls.

Heating. If steam leveling is off, the controls ramp the digester temperature to its cooking temperature in the specified heat time. If steam leveling is on, digester heating consists of two phases: (a) control before the end of the spacing interval; and (b) control after the elapse of the spacing interval. The spacing interval time is computed by the production scheduler to achieve the specified production rate within the limits of a steam constraint. During the first phase (after steaming commences but before the next digester starts steaming), steam flow to the digester is regulated to attain constant steam draw from the headers. During the second phase (after the next digester has started steaming), the temperature is ramped to the cook temperature target without constraints on the rate of steam flow.

Feedforward and feedback controls are used during the second phase to attain the required temperature-rise rate and the target cook temperature. The steam required to attain a specified rise rate is computed based on an energy balance around the digester during each digester cycle.

Cooking. During the initial heating phase, the digester behaves as an endothermic reactor, i.e., heat is required to maintain or increase the temperature. However, during cooking, the delignification reactions are exothermic. This means that temperature control must be able to reduce temperature if the cook temperature is too high. Batch digesters are not supplied with a means to reduce temperature except by relieving pressure. Thus the temperature is increased by steam addition and decreased by steam relief.

Blowing. The control system estimates the time to blow based on the cook temperature and the delignification model. At 5 min before predicted blow time, the system requests permission to blow. Anytime during this 5-min period, the operator can enable the automatic blow function.

Before a blow commences, the system verifies that its assigned blow tank has adequate volume, that no other digesters are blowing, and that digester pressure is sufficient to achieve a clean blow. When these conditions are met, the system automatically opens the blow valve.

The system monitors digester pressure as the primary variable to determine when the blow is complete. A hardware interlock on the cap valve prevents the cap from opening prematurely. The computer issues commands to close the blow valve and to open the cap valve when the digester pressure is below a threshold, providing the digester has been in the blowing state for at least 3 min. The system also is capable of issuing a blow "hold" command, which occurs either on operator demand or if the prerequisite blow conditions are not satisfied.

Inadvertent opening of any of the controlled valves is a potential hazard. The interlock functions are performed on a separate DCS board for each digester. Consequently, the interlocks are independent for each digester. The system provides the necessary security by requiring redundant signals for blow- and cap-valve status.

Relieving. The digester relief valve removes air and volatile compounds liberated during the heating phase. The position of the relief valve is controlled so that the flow of relief gas is proportional to the rate at which noncondensible gases are liberated. The ASME (American Society of Mechanical Engineers) steam tables are used to determine the saturation pressure based on the measured temperature. This is further compensated for MSL (mean sea level) elevation, boiling-point rise, and target excess pressure.

Turnover. This function detects and corrects inadequate digester convection. If the absolute value of the temperature difference between the lower digester temperature and the upper temperature is greater than an operator-entered value, and if the digester pressure exceeds 20 psig (pounds per square inch gauge), then the steaming and relief valves close and the blow-back valve opens for a preset period, typically 30–60 s.

Shakeup. Just prior to the blow, direct steam is injected into the digester. This serves to loosen any uncooked chips in the discharge cone. At Hopewell, this function is not enabled because the digesters blow cleanly without it.

Blow-back control. The blow-back control system automatically purges the relief screens. The operator sets the blow-back interval through the video screen. The relief valve is closed and the blow-back valve is opened during blow back. A final blow back automatically occurs at the end of a blow. The end-of-cook blow back ensures that the screens are clean before the next charging cycle begins.

House control

The house-control functions consist of liquor charging and chip loading.

Liquor charging. The software that controls liquor charging runs in a single board at the DCS level of the system. It controls the amount of white and black liquor required to attain the targeted chemical-to-wood and liquor-to-wood ratios. The white-liquor EA, the chip mass charged to the digester, and the chip moisture are used to compute required white-liquor volume. The targeted white-liquor volume, chip moisture, and wet-wood weight are used to compute the required black-liquor volume.

7. Video frame for production scheduling

SCHEDULER

Next cook # 267

	Asked	Prop	Current target	Current value	Units
Total cooks/day	24.0	24.0	24.0		
BT1 cooks/day	8.7	8.7	8.7		
BT2 cooks/day	15.3	15.3	15.3		
Heat time max	70.0	70.0	70.0		min
Heat time	55.0	70.0	70.0		min
Cook time		30.0	30.0		min
BT1 # in service	4.0	4.0	4.0		
BT2 # in service	7.0	7.0	7.0		
Idle time		49.0	49.0		min
Spacing	60.0	60.0	60.0	51.1	min
Max avail steam	160.0	160.0	160.0		mpph
Avg steam		20.9	22.0	16.0	mpph
Ave # heating		1.2	1.2	4.2	
Type	Prodution OK		Prodution OK		

Heat time and cook tmp opt req heat time and cook tmp opt on

White- and black-liquor charging begin after chip loading starts. **Figure 5** is a typical example of a charging display on the operator's screen. After initial liquor charging, the capping valve is automatically closed, and a final liquor top-off is performed.

Measurement of EA strength. The white-liquor strength varies throughout the day. **Figure 6** contains typical data logged by the operator. For any digester charge, the error in EA strength could be 5 g/L or more, which could cause an error of up to two kappa number units, as shown in Fig. 3.

An on-line EA sensor is located downstream of the white-liquor fill pump. The sensor titrates a trapped sample of liquor with CO_2 gas. Each titration takes 5-7 min, depending on the liquor strength. The sensor titrates one side of a dual-cell vessel with industrial-grade CO_2. Heat is liberated by the neutralization reaction, causing the titrated cell temperature to rise. The end point is determined when the temperature rise stops. The amount of CO_2 consumed is directly proportional to the EA.

The sensor is calibrated by inputting laboratory test values of samples collected during the purging cycle of the EA sensor. These data are used recursively in a least-squares manner to determine the correlation coefficients for the calibration curve. The sensor can be recalibrated at any time by entering fresh laboratory data. The sensor's accuracy on white liquor is better than 2% over the entire measurement range.

Chip loading. The mill's chip-loading system is totally automated. The chip tripper is positioned to the next digester in sequence. Delivery commences when the operator gives the "charge" permit. Either a gamma gauge or a weightometer accumulator contact causes a time-delayed shutdown of the conveying system, thus assuring that all conveyors are free of chips.

Optimizing controls

The optimizing controls run in the area computer. The software is written so that it can be modified as needed on-line.

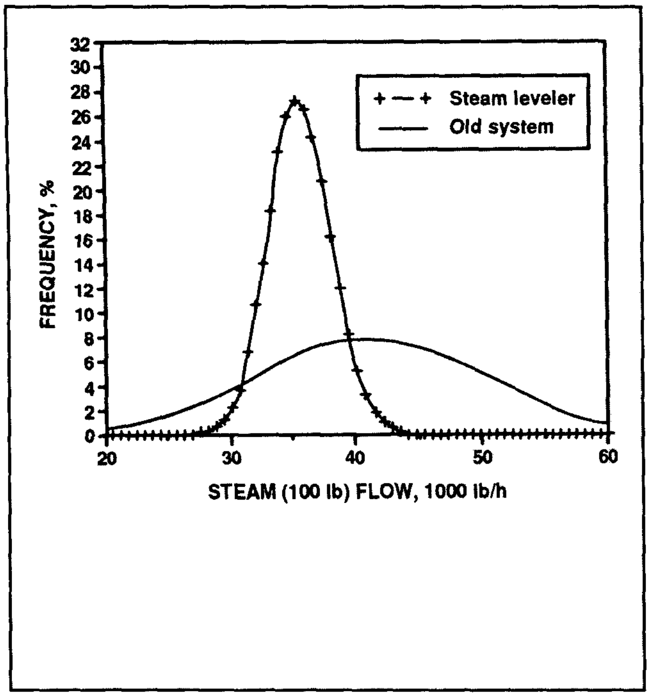
Steam leveling. The steam-leveling module eliminates most of the boiler steam swings caused by overlapping heating phases. This is done by adjusting digester steam flows during the first portion of the heating cycles. Priority use of the steam is allocated to digesters after completion of the spacing interval to enable the target cook temperature to be attained. If required, individual digesters can be suspended from the steam leveler and heated at a fixed rate.

Kappa number control. The kappa number module executes control each minute and predicts a new cook temperature or a new blow time if the new cook temperature exceeds a limit. The actual charged chemical-to-wood and liquor-to-wood ratios are used in the control calculations. Since the Chari model cannot be solved analytically for time or temperature (the *H*-factor is an integral equation), a modified Newton-Raphson solution method is used to determine new target cooking parameters.

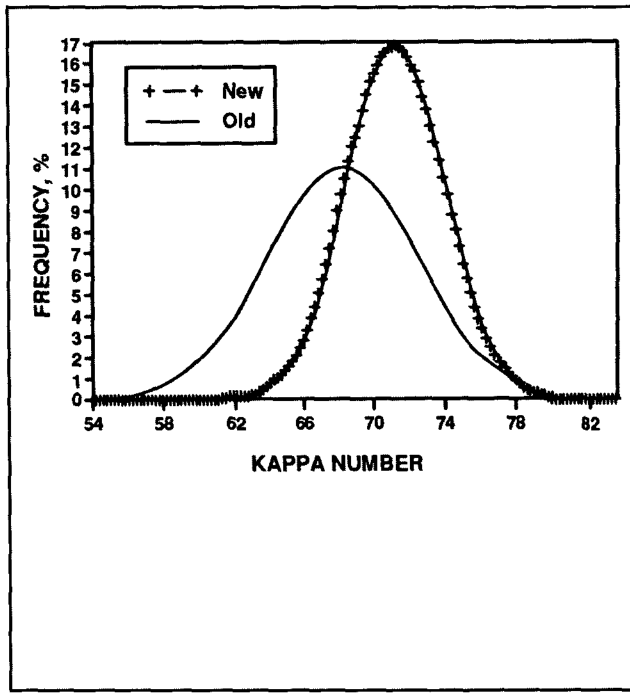
The blow-line kappa number tests update the kappa number control model. Details of this procedure are outlined by Wells (*4*).

Production scheduling. The production scheduler sets the digester cooking parameters so production rates are either at the specified target or maximized within the operating limits, while minimizing energy costs and maximizing liquor impregnation time. The target kappa number combined with the actual chemical-to-wood and liquor-to-wood ratios establish the cook time and temperature required. Values of the charging and blow times are determined by the system software based on the average performance of the system over the last several days. These values are then used in conjunction with the heat and cook

8. Distribution of steam-flow rates for old and new control systems. The new steam leveler reduced variability of steam flow by 72%.



9. Distribution of kappa number for old and new control systems. Average kappa number increased by 2.87, for a 0.72% increase in pulp yield.



times to determine if the schedule can be achieved. The scheduler also calculates the average house steam demand.

Figure 7 shows the operator's scheduler screen. The operator enters the total cooks/day, the number of digesters in service for each blow tank, and the maximum available house steam flow rate. If the computed cycle time or steam flow constrain the operator's proposed schedule, the limiting item will be highlighted. The operator can either accept the computer-proposed alternative schedule or can change the constraining item—the maximum steam limit, the grade recipe, or the species/grade split—to establish the desired production.

The operator can evaluate alternative schedules and production rates without influencing the current operation. This assures optimization of the production schedule while allowing the operator to ask "what if" questions without affecting production. There are two modes of scheduling available when the required production is less than the digester or steam-limit constraint: energy optimization and quality optimization.

Energy optimization. Whenever the "idle full" time is greater than zero, the cooking schedule can be adjusted to minimize steam consumption at the requested production rate. "Idle full" time is added to the cook time, and the cook temperature is reduced to its minimum value while maintaining target kappa number.

Quality optimization. This control mode reduces any remaining "idle full" by increasing the heat time up to its maximum value. The "idle full" time left over from the energy-optimization control is added to the heat time. If both modes are requested, the energy control will take precedence to reduce the cook temperature preferentially.

Results

Relaxation of charging bottlenecks

During high production rates, the digester house is charge-limited. The system knows the next digester to be charged and hence begins tripper movement before the liquor top-off cycle is completed. This action minimizes the charging cycle, allowing the mill to maximize the production rate.

Reduction in energy consumption

The house steam-flow-rate distributions for the previous and the new control systems are shown in **Fig. 8**. These curves were generated by fitting a Gaussian curve to the histogram of actual process data. The standard deviation of the steam flow rate is 72% less than that of the old steam leveler, and the average steam consumption is about 5000 lb/h less at the same production rate. This lower average is probably due to the differences in relief control between the old and the new systems.

Reduction in kappa number variations

Based on data collected during the first several months of operation, kappa number variation under the new control system has been reduced by more than 30% compared with the former computer-control system. It is expected that variation will continue to be reduced. Gaussian curves fitted to the actual kappa number data before and after the new computer was installed are shown in **Fig. 9**. The average value for kappa number has increased by more than two units, resulting in a substantial improvement in yield.

Conclusion

An integrated distributed control system (DCS) was installed in a batch digester house. Most control functions are executed in the low-level DCS portion of the system. The high-level controls— kappa number, scheduling, and steam leveling—are executed in the area computer. This design provides full local control in the event that the main computer fails. A failure anywhere else in the system will affect only the digester involved and consequently will not shut down the digester house.

The digester-house control system is an application of the hierarchical-control design philosophy. This technology has long been used in the petrochemical and steel industries and has now been demonstrated to apply equally well in the pulping industry.□

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