Optimization of combustion air delivery

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ABSTRACT

The load on a 1970 vintage recovery boiler caused accelerated fouling in the upper furnace, unstable combustion in the lower furnace, and TRS emissions that were difficult to control. A contractor worked with the mill to determine the best way to increase combustion air delivered at or above the liquor guns. Evaluation of several configurations by computer modeling led to the use of air nozzles on both the front and rear walls at the liquor gun level. The primary benefits of the modifications were reduced carryover, less plugging of flue gas passages, reduced TRS emissions, and more stable combustion in the lower furnace.

Application:

Small changes in air delivery for a very heavily loaded recovery boiler can have significant effects on boiler operation. Introduction of quaternary air at the liquor gun level can reduce TRS emissions and decrease plugging.

A RECOVERY BOILER INSTALLED IN 1970 was designed to burn 1.09 million kg/day (2.4 million lb/day) of virgin liquor solids with a steaming rate of 178,000 kg/h (392,000 lb/h) at 101.7 bar (1475 psi) and 496°C (925°F). As with several boilers built in the late 1960s, the boiler is short compared with more modern units having similar firing rates. **Figure 1** shows a schematic of the recovery boiler. Many modifications were made to the unit in the late 1980s and early 1990s including modifications to the air and liquor delivery systems, addition of a new screen, and the installation of a new economizer.

The modifications allowed operation of the boiler at a virgin solids loading rate of more than 1.36 million kg/day (3.0 million lb/day) of liquor solids *(1)*. The furnace is approximately 8.5 m (28 ft) wide and 8.2 m (27 ft) deep. Converting the solids input to heat input on a cross-sectional area basis gives a hearth loading rate of more than 3470 kW/m^2 (1.1 million Btu/hr·ft^2).

Cross-sectional heat input rates provide a comparison for recovery boilers of different sizes and designs *(2, 3)*. **Figure 2** shows the design heat input rates for many recovery boilers reported in the literature *(2, 3)*. Open circles show the data points for design conditions. The dark circle is a test point for the boiler considered in this paper taken in 1995. Current operation of the boiler is significantly above the design point of this unit and considerably above the design of nearly all other recovery boilers.

One interesting exception to the general design heat input rate of 2840-3150 kW/m^2 (0.9-1.0 million Btu/hr·ft^2) is a unit from the early 1970s. The unit had a design solids firing rate of 1.8 million kg/day (3.97 million lb/day) and a heat input rate of 343,000 kW (1,170 million Btu/h) translating to 3690 kW/m^2 (1.17 million Btu/hr·ft^2). The unit was installed and operated satisfactorily for many years with a conventional two-level air system.

For the boiler considered here, operating at the highly loaded condition meant that the boiler needed water washing several times a year. This was partly due to flue gas temperatures leaving the furnace approaching 1093°C (2000°F) and a large amount of liquor particle carryover. Other boiler operating issues included variable levels of Total Reduced Sulfur (TRS) compounds of approximately 2–3 ppm but with peaks up to 15 ppm. Carbon monoxide (CO) concentrations were 500–1000 ppm with excess oxygen levels at approximately 2.5%.

Combustion in the lower furnace was unstable with a regular furnace blowback through liquor gun openings. The regularity of the puffs—approximately once per minute—prompted review of furnace draft control and the potential for the forced or induced fans to be operating at an unsteady point on their operating curve. No mechanical sources for puffing were obvious. Observation of other recovery boilers indicated a link between delivering black liquor to the boiler at a temperature above the flash point and boiler puffing.

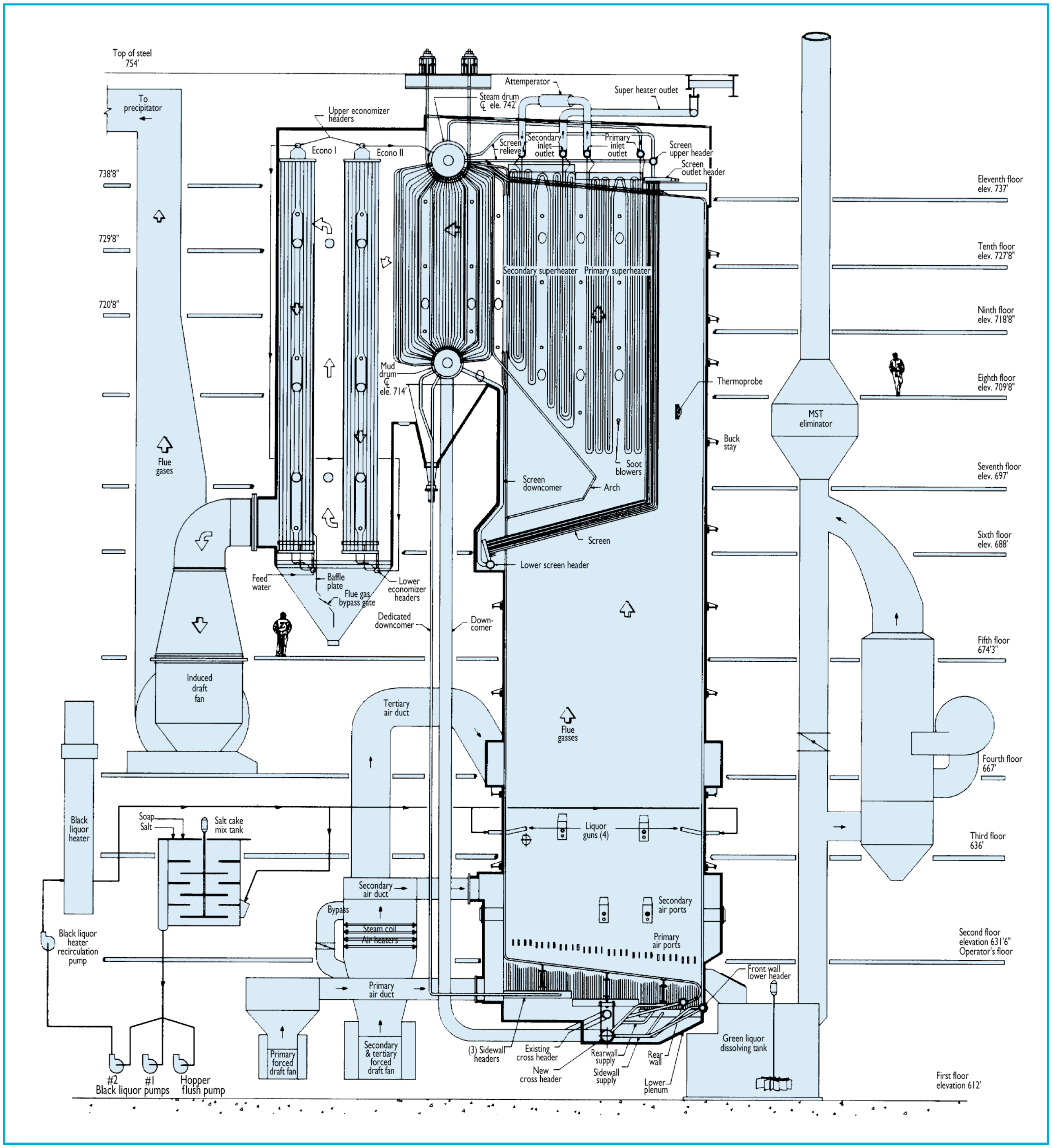
The operating problems prompted the mill to consider some unconventional changes to air delivery. In early 1994, the mill contracted for help to design and supply air system modifications to deliver additional combustion air at or above the level of the liquor guns.

COMBUSTION AIR DELIVERY

Almost universally, all new or retrofit recovery boilers have three levels of combustion air. Some notable exceptions do exist.

Four-level air systems

A method implemented in the late 1980s involved staggering the levels of tertiary air *(4)*. Tertiary air nozzles were located on the front and rear wall at two elevations. The upper rows of tertiary air ports were



1. Schematic of the recovery boiler

approximately 1.2 m (4 ft) above the lower ones. Air flow modeling indicated that this configuration was superior to the more conventional design. Direct observation of this unit and discussion with operating personnel indicated it was operating satisfactorily at a high load. To our knowledge, this was the only implementation of this type of air configuration.

Another development in alternative air system arrangements for recovery boilers came in the late 1980s *(5)*. This was the Overlapping Multilevel Air System. The arrangement incorporated secondary and tertiary ports both at two elevations. One level angled down, and the level on the opposite wall angled up. We are not aware of any boilers in North America using this configuration.

In the early 1990s, Feck *(6)* reported the use of a fourth level of air above the conventional tertiary air level. The boiler had load burners used as a supply of quaternary air.

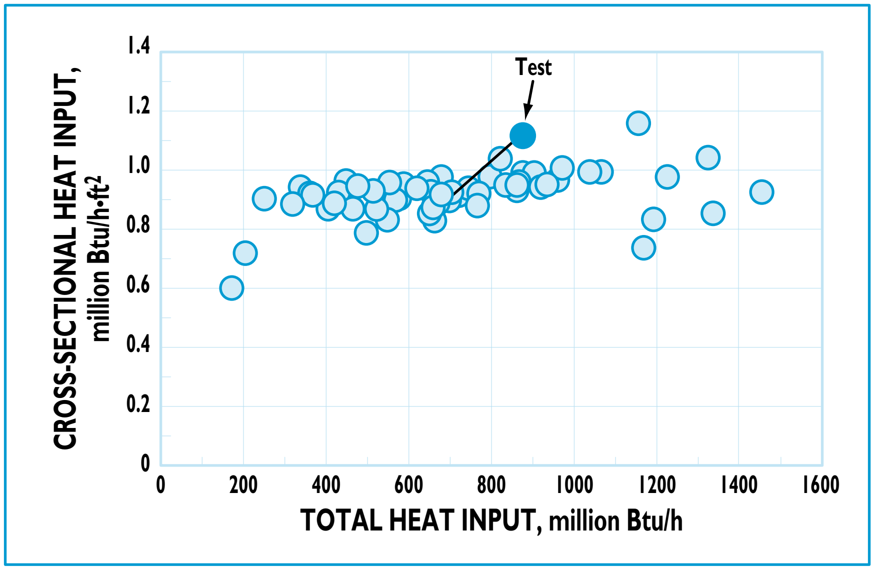
The paper described boiler air spits when operating at the maximum rated capacity of approximately 24% primary, 45% secondary, 14% tertiary, and 17% quaternary air. As the load ranged from 75% to 125% of maximum rated capacity, the strategy was to vary only quaternary air while keeping the air flow at other levels constant. At the rated capacity, approximately 30% of air would be above liquor guns.

The work was partly necessary to control NO_x emissions from the recovery boiler. The staging of air and liquor was an attempt to reduce NO_x from the oxidation of nitrogen in the air at high temperatures as happens in other types of combustion processes with other fuels. While studies since then have concluded that it is doubtful that thermal NO_x is an important source of NO_x emissions from recovery boilers *(7, 8)*, the work was an interesting study in the use of control charts and operator training to limit variability in boiler operation.

Increased tertiary air

Hiner discussed the effect of tertiary air on liquor chemistry *(9)*. The data from the boiler tested indicated that the air splits—among other factors—changed the fly ash chemistry. He attributed this to an increase in the tertiary air amount that decreased the flue gas temperatures in the lower furnace. Another paper *(10)* described approaches to modifying the ash characteristics in a boiler experiencing rapid fouling of the superheater. Increasing the tertiary air there had only a moderate impact on the fouling rates.

The effect of increased tertiary air will be specific for each boiler. Boiler trials are often not conclusive since the ideal air splits may not be possible because of limitations of the existing equipment, upset conditions that may not be tolerable for mill production requirements, and data that is often difficult to interpret. For the Escanaba boiler, we therefore decided to use computer modeling to identify preferred arrangements for combustion air delivery as part of the design phase of the modifications.



2. Cross-sectional heat input as a function of total heat input

	Split	Temperature, °C (°F)	No. of Ports	Windbox pressure, kPa (in. wg)
Primary	43%	107 (224)	128	1.5 (6.2)
Secondary	43%	93 (200)	20	3.2 (12.8)
Tertiary	14%	93 (200)	6	3.8 (15.3)

I. Phase I air delivery conditions

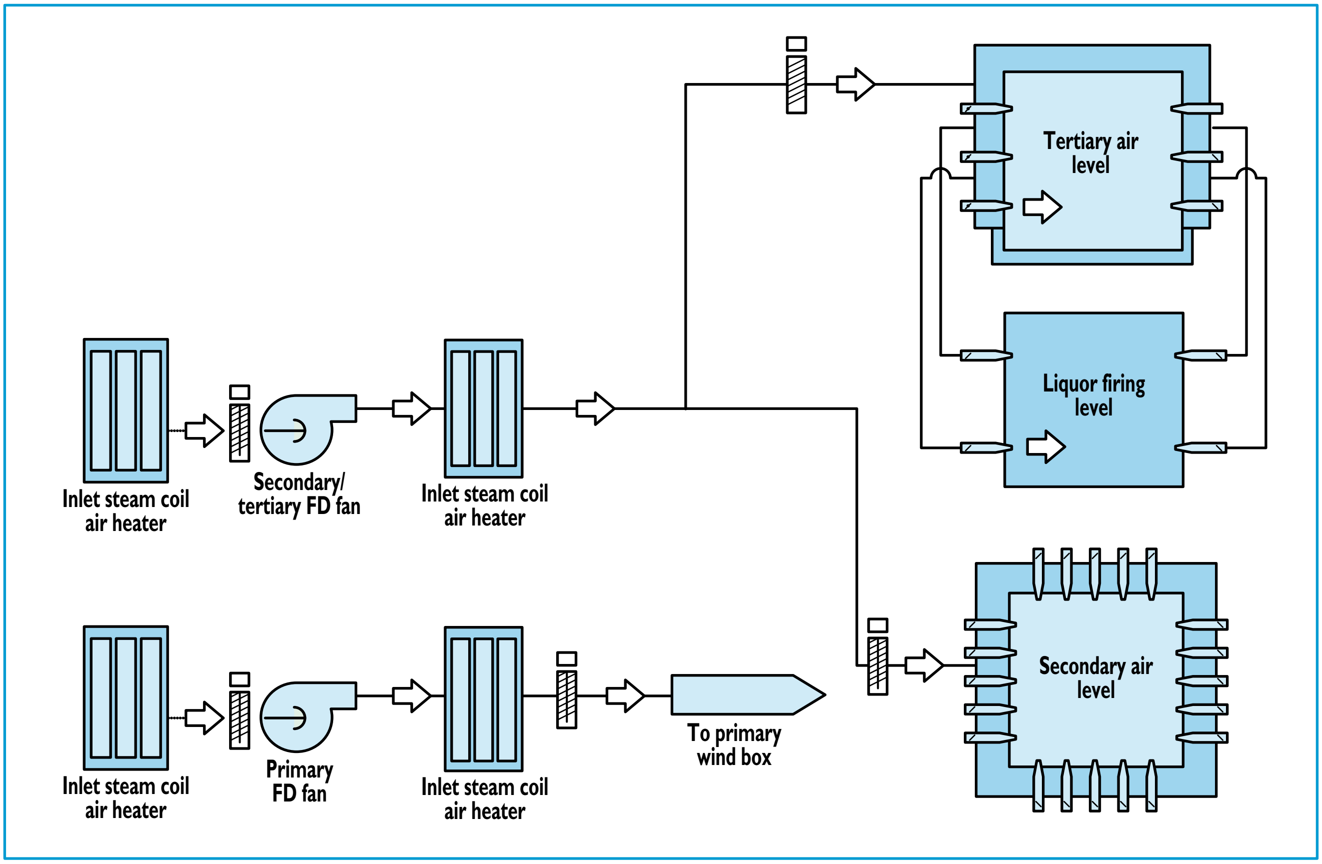
Applications of computer modeling

In the late 1980s, two essentially parallel programs set out to develop recovery boiler models based on computational fluid dynamic (CFD) packages. These initial modeling efforts demonstrated the ability to simulate gas flow patterns inside the furnace cavity and the resulting effect on liquor combustion. The work of Karvinen *et al. (11)* did not iteratively link the gas phase and the liquor phase. This allowed simulations with more modest computational requirements. The work of Grace *et al. (12)* used a fully coupled solution that required higher levels of computational resources.

Computer modeling is now an established technique to conduct parametric analyses of recovery boilers. Any recent symposium on recovery boilers will have many such papers. Comparison of fully integrated gas phase and liquor phase combustion models—giving calculated gas temperatures, chemical compositions, etc.—with isothermal models *(13)* using prudent assumptions for flue gas temperatures and compositions showed that isothermal models can be adequate. Isothermal models appear to be adequate for screening several different potential air system arrangements. Factors other than the degree of coupling limit the ability of any of the models—fully coupled or isothermal—to give representative results. In particular, the initial black-liquor-drop diameters are critical to the accuracy of the models.

Modeling black liquor sprays

Using the approach described in an earlier paper *(14)*, we used the relationship in Eq. 1 to predict the average drop diameter from liquor deliv-



3. Flow diagram of phase II combustion air conditions

Case	Inorganic carryover, %
I	12
II	10
III	7.8
IV	5.0

II. Inorganic liquor carryover

ery conditions. In the equation, the base conditions use laboratory studies at the Institute of Paper Chemistry on black liquor spray nozzles *(15)*.

$$Dmm = D_{mmb}(\mu/\mu_b)^a(V_b/V_a)_b(D_n/D_{nb})^c \quad (1)$$

where

D_{mm} = calculated mass mean diameter
D_{mm} = base mass mean diameter
μ = calculated liquor viscosity
μ_b = base liquor viscosity
V_b = calculated drop velocity
V = base drop velocity
D_n = nozzle diameter
D_{nb} = base nozzle diameter
a = viscosity dependency
b = velocity dependency
c = diameter dependency.

When the liquor temperature is above the flash point as with the boiler considered here, one must account for this effect. Some treatments have used an empirical parameter to reduce the average drop size.

Our approach for determining the effect of flashing on the drop diameter involved first calculating how far the liquor temperature is above the flash point and then predicting the fraction of steam that will be flashed from the liquor in the nozzle. This sets the volumetric flow of the two-phase mixture out of the nozzle and a two-phase friction factor. These parameters determine the drop velocity that subsequently affects the average drop diameter. This technique removes one level of empiricism from the calculation.

This approach also yields an important insight into the effect of flashing. As the liquor temperature increases above the flash point, the friction losses in the nozzle also increase. Consequently, less liquor can be delivered through the nozzle at the same differential pressure. In practice, the result is often use of a larger liquor nozzle so the effect of flashing and larger nozzle diameter cancel each other.

RECOVERY BOILER IMPROVEMENT PROGRAM

This paper describes the use of a computer model using a coarse grid to simulate the conditions for an isothermal gas with varying delivery conditions. The calculated gas flow predicted the trajectory and combustion behavior of liquor drops and provided information to make inferences concerning turbulence and mixing on combustion.

Improvements to the recovery boiler combustion and air delivery system occurred in the following stages:

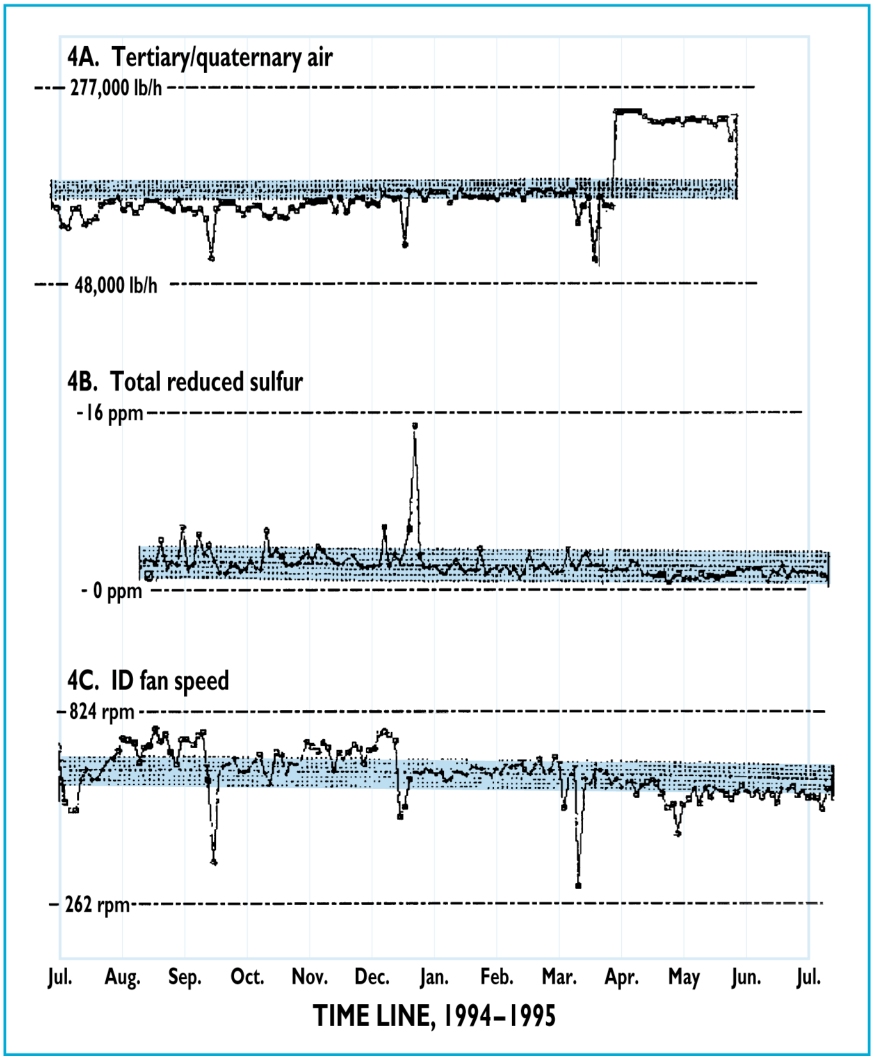
- Modifications to the air and liquor systems before 1994
- Phase II installation of quaternary air with four air nozzles at the liquor gun level in 1994
- Phase III installation of four additional quaternary air nozzles in 1995
- Phase IV installation of four additional tertiary air nozzles planned for 1996.

Phase I to phase II transition

Table I summarizes the air delivery conditions after Phase I modifications. The mill wanted to increase the fraction of tertiary air but imposed several constraints. If possible, the mill wanted to use existing tube bend openings, limit new ducting for air supply, and install the equipment during an upcoming shutdown only a few months away. At the time of the liquor system modifications in the late 1980s, tube bends for additional liquor gun openings were installed. Each wall had three liquor gun openings, but only the center one on each wall was used. The secondary and tertiary air systems were fed from the same fan, and the air pressure to the tertiary air level was limited to approximately 4.2 kPa (17 in. wg). Increasing tertiary air would therefore require additional openings.

Approximately ten different computer simulations were run with varying air splits and locations of the additional nozzles. From these, we selected the following four representative cases:

- Case I: Pre-1994 modification conditions
- Case II: 10% combustion air at quaternary air level with nozzles opposed
- Case III: 12% combustion air at quaternary air level with nozzles opposed
- Case IV: 12% combustion air at quaternary air level with two nozzles angled in 10°.



4. Trends in boiler operation before and after quaternary air

	Split, %	Temperature °C (°F)	No. of ports	Windbox nozzle pressure, kPa (in. wg)
Primary	37	107 (225)	128	1.2 (5)
Secondary	37	93 (200)	20	2.5 (10)
Tertiary	14	93 (200)	6	3.5 (14)
Quaternary	12	93 (200)	4	3.5 (14)

III. Phase II conditions

Table II summarizes the smelt carried over for the four cases. Simulations of the resulting gas flows from air nozzles at the liquor gun level on the front and rear wall showed strong recirculation zones directed toward the liquor gun openings on the side walls. Since the boiler was already experiencing some puffing, we decided to angle one air nozzle in on each wall by 10° to move the recirculation zone. An additional benefit of angling the air nozzles was to change the flow patterns to reduce the carryover.

The computer modeling work showed that the amount of carryover could be reduced by half with only

	Split, %	Temperature °C (°F)	No. of ports	Windbox nozzle pressure kPa (in. wg)
Primary	30	99 (210)	128	1.1 (4.3)
Secondary	20	93 (200)	8	1.7–2.7(7–11)
Tertiary	20	93 (200)	6	3.7 (15)
Quaternary	30	93 (200	8	3.2 (13)

IV. Phase III conditions

Liquor	Units	Design	1995 Test
Flow	L/min	-	1037
	(gpm)	(274)	
Virgin solids burning	million k/day	1.09	1.42
rate	(million lb/day)	(2.4)	(3.12)
Temperature	°C	-	127
	(°F)	(260)	
Pressure	bar	-	1.3
	(psig)	(18.9)	
Solids content	%	60	71.9
Steam			
Flow kg/h	178,000	245,000	
	(lb/h)	(392,000)	(540,000)
Drum pressure	bar	106	105
	(psig)	(1540)	(1530)
Header pressure	bar	102	101
	(psig)	(1475)	(1460)
Final temperature	°C	496	734
	(°F)	(925)	(861)
Feedwater			
Temperature to	°C	186	150
economizer	(°F)	(367)	(302)
Temperature from	°C	269	254
economizer	(°F)	(516)	(489)
Combustion air			
Total air flow	kg/h	245,000	303,000
	(lb/h)	(541,000)	(669,000)
Primary air flow	kg/h	-	144,000
	(lb/h)	(317,000)	-
Secondary air flow	kg/h	-	83,000
	(lb/h)	(182,000)	-
Tertiary/quaternary air	kg/h	-	77,000
flow	(lb/h)	(170,000)	-
Flue gas			
Excess air	%	10	-
Excess oxygen, east	%	-	2.4
Excess oxygen, west	%	-	1.6
Carbon monoxide	ppm	-	90
Boiler bank outlet	°C	418	416
temperature	(°F)	(785)	(780)
Economizer outlet	°C	238	229
temperature	(°F)	(460)	(445)

V. Recovery boiler operating data

minor change to the air delivery system. Two factors caused this. There was a straight dilution effect. Delivery of less air below the liquor guns gave lower upward gas velocities with less carryover. The second factor was that different arrangements for air delivery changed the flow patterns. For this boiler, the most beneficial flow pattern was one where the entrained liquor particles swirled away from the center of the boiler toward the walls so that the liquor would not carry over.

After the modeling work, the necessary duct work and air nozzles were fabricated according to the flow schematic shown in **Fig. 3**. **Table III** summarizes the air delivery conditions.

Startup of the boiler after the installation of the quaternary air system resulted in almost immediate benefits in the levels and variability of TRS. **Figure 4A** shows a trend chart for tertiary air flows before the modifications and tertiary air and quaternary flow afterward. The chart is for approximately one year. **Figure 4B** shows the levels of TRS for the same period. The levels stabilized with a decrease in the average levels.

Another benefit was in reduced plugging of the unit. **Figure 4C** shows the induced draft fan speed over the same period as the other variables. For the first part of the curve, the fan speed can be seen to increase as the gas passages become plugged. After approximately 2.5 months, the boiler required a water wash. When the boiler returned online, the plugging restarted. Three months passed before requiring a water wash. After the air system modification, the boiler ran more than three months with no noticeable increase in fan speed or plugging.

Phase II to phase III transition

The success of the quaternary air system required only a small investment. The benefits led the mill to investigate further improvements.

The mill installed four additional quaternary air nozzles—two on the front wall and two on the rear wall at the liquor gun elevation. The Phase III modifications occurred in the middle of 1995 using the conditions summarized in **Table IV**.

After the Phase III modifications, there was additional boiler testing. **Table V** shows test conditions and the design values.

The liquor solids burning rate was 30% over design. The steaming rate surpassed this and was 38% over design. This was partly due to an increase in boiler thermal efficiency. As expected, the greatly increased loading rates gave higher flue gas temperatures.

FLUE GAS TEMPERATURES

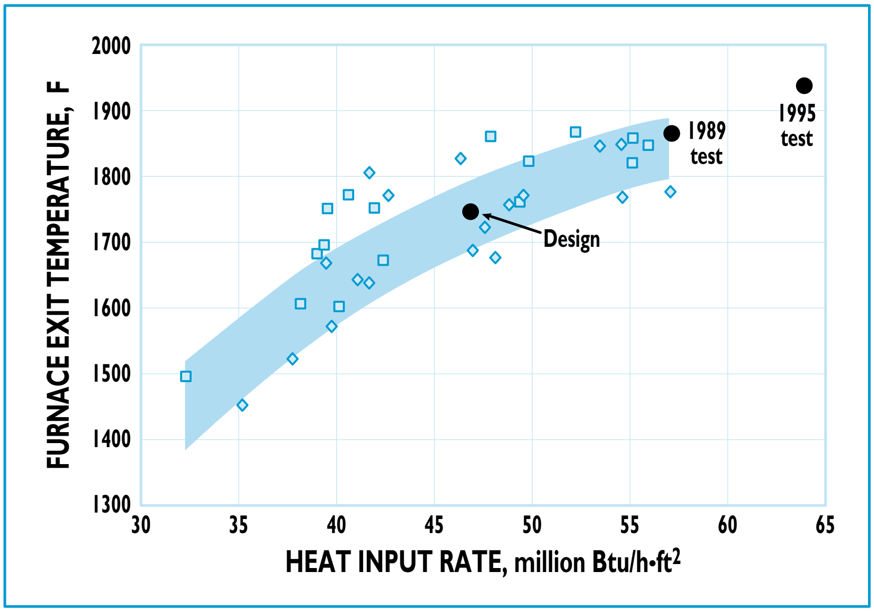
The flue gas temperature leaving the furnace cavity had always been high due to the short height of the unit. **Figure 5** shows a plot of the measured flue gas temperature at the furnace outlet as a function of the heat released per unit area of heat transfer surface. The plot shows many test values for other recovery boilers and the design and two test values for the Escanaba recovery boiler. At the 1989 conditions, the boiler was at the upper range of other recovery boilers. The recent heat input rates are significantly above other units we have tested.

The very high heat input rate results in flue gas temperatures leaving the furnace of approximately 1066°C (1950°F). Note that the temperature follows the same general curve as for other boilers over a very wide range of heat input rates. Modifications to the air delivery system also do not appear to affect the furnace outlet temperature on a heat transfer surface area basis.

Observation of the layout of the unit shows a large screen and superheater that results in moderate temperatures into the generating bank section. For the test conditions in 1995, the average flue gas temperature at the generating bank inlet was 660°C (1200°F).

	Units	1989	1995
Solids	%	66.6	69.4
Higher heating value	kJ/kg	14,940	14,600
	(Btu/lb)	(6425)	(6280)
Carbon	mass %	35.8	34.1
Hydrogen	mass %	3.52	3.74
Oxygen	mass %	36.5	38.5
Sulfur	mass %	3.21	4.22
Chloride	mass %	0.70	0.26
Sodium	mass %	18.3	19.3
Potassium	mass %	0.97	1.66

VI. Black liquor analyses—concentrator product



5. Furnace outlet temperature as a function of heat loading on a heat transfer surface area basis

Liquor chemistry

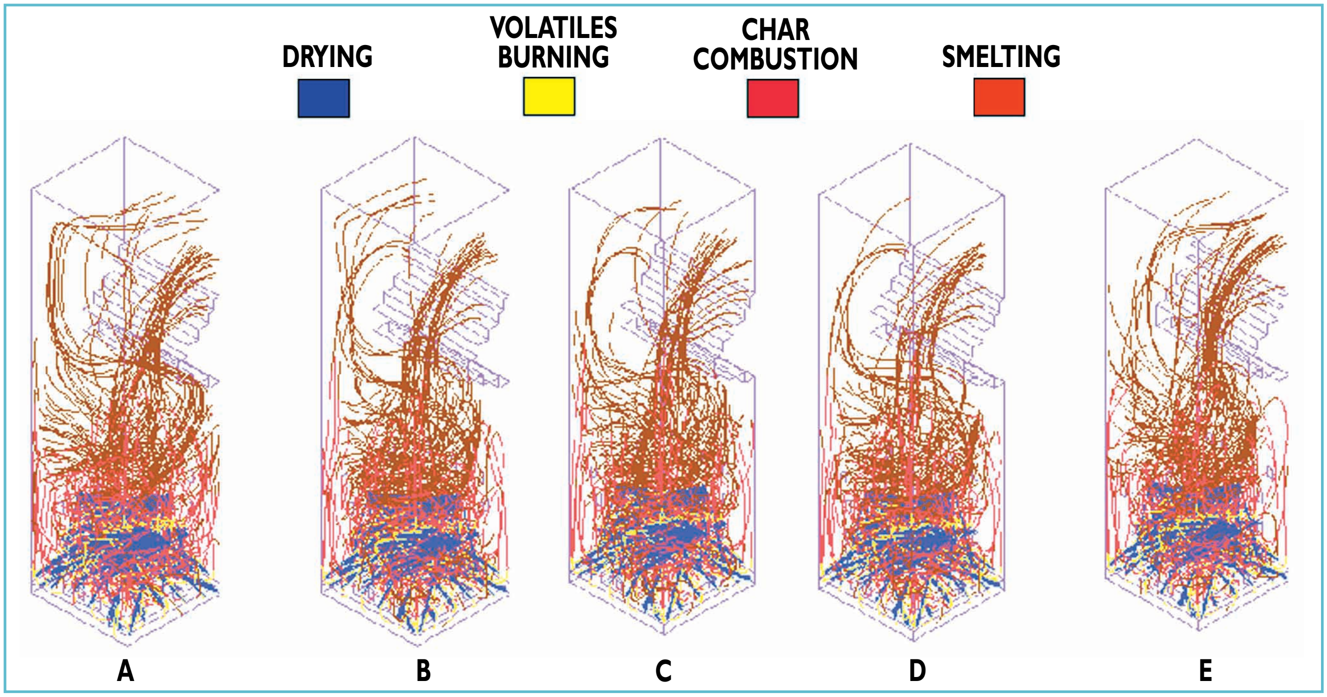
Table VI is a comparison of the past and present liquor chemistry. The table indicates a trend toward higher solids content liquors with a decrease in liquor heating value. Note that the liquor heating value fluctuates as the mill alternates between hardwood and softwood cooks.

Another item is that sulfur levels are higher. One effect of sulfur is its influence on fly ash chemistry. Subtle changes in sulfur levels in the black liquor may lead to much larger changes in fly ash chemistry.

	Units	1989	1995
Sodium	mass %	33.9	33.4
Potassium	mass %	4.64	4.35
Chloride	mass %	2.81	1.80
Carbonate	mass %	12.9	12.5
Sulfate	mass %	45.5	47.9
Sulfide	mass %	0.27	0.01
pH	(5% wt. solids)	-	11.4

VII. Fly ash analyses—economizer outlet

Table VII shows a comparison of the chemistry of fly ash collected at the economizer outlet for the test periods in 1989 and 1995. The ratio of sulfate to carbonate in the fly ash—generally a reliable indicator of the complex interactions of liquor sulfur levels and overall fuming



6. Trajectories and combustion of liquor drops

rates—shows little change. The chloride levels have decreased, but the level is moderate and should not affect plugging rates.

Phase III to phase IV

Despite the extremely high heat input rates to the boiler, the mill has continued to pursue modifications that would give additional margins for run time between water washes and decreased levels of air emissions. To achieve this, we have modeled several additional cases that would incorporate four additional air nozzles at either the tertiary or quaternary level.

Figure 6 illustrates the liquor drop trajectories and burning behaviors for five different cases. These include (A) the current (Phase III) configuration, (B) two tertiary nozzles on each side wall, (C) air nozzles on the side walls but angled down by 15°, (D) two of the air nozzles angled down and in, and (E) two additional tertiary air nozzles on the front and rear walls. Liquor sprays in through four liquor nozzles centered on each wall.

The plots show modest differences in the amount of carryover for the five cases. Tabulation of the amounts shows that the Case C conditions gave the least carryover. Checks on turbulence levels showed that mixing would also be more intense with the Case C arrangement. A new design implemented in 1966 incorporates these features.

SUMMARY

This case history of a very heavily loaded recovery boiler has shown that small changes in air delivery can have significant effects on boiler operation. Introducing quaternary air at the liquor gun level reduced TRS emissions and decreased plugging rates. Incremental changes in air delivery occurred in three successive steps.

At each phase, computer modeling supported the design of the additional air nozzles. This work was instructive in identifying locations for the new air nozzles and air splits.

The success and unique character of the approach led to a patent application to cover the combustion air delivery system. For the efforts to improve the air emissions from its recovery boiler, the mill using it received special recognition from AFPA with the 1995 National Award. **TJ**

KEYWORDS

Air, air jets, boilers, combustion, computers, emission, furnaces, gas, heating equipment, Michigan, nozzles, recovery furnaces, simulation, upgrading

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