# Recovery boiler fireside capacity: An update of theory and practice

**John F. La Fond, Arie Verloop, and Johan H. Jansen**

*ABSTRACT: Increases in recovery boiler firing capacity can often be obtained through upgrade of the air and liquor delivery systems to achieve improved combustion. These increases can be achieved without pressure part modifications of the convective sections of the boiler. Reduced water wash frequency, less total reduced sulfur (TRS) emissions, and improved reduction efficiency are other benefits that result from combustion improvements. The means of accomplishing improved combustion in recovery boilers has been an area of intense interest over the past few years as recovery boiler capacity has limited mill expansion efforts.*

*This paper describes the limitations to recovery boiler capacity upgrades, discusses how improved combustion can allow an increase in solids firing capacity, describes the means of achieving combustion improvements, and provides a summary of upgrade efforts as examples of previous successes.*

*KEYWORDS: Capacity, combustion, performance evaluation, recovery furnaces, theories, upgrading.*

Due to its large scale and high capital expense, the recovery boiler often becomes the bottleneck in kraft mill expansion efforts, limiting the ultimate level of pulp production and mill profit. An incremental increase in recovery boiler capacity is very attractive economically due to the profitability of increased pulp production without major capital and operating expense. Most often, the cost of increasing the capacity of recovery boilers can be recovered in less than one year.

Recent efforts to reduce mill dioxin emissions through implementation of the oxygen delignification process have resulted in higher solids loading to the recovery boiler without increased pulp production. In such cases, a recovery boiler upgrade may be necessary to maintain current production levels.

To be considered truly successful, increased capacity must be accomplished without jeopardizing safe and reliable operations. To achieve increased capacity without exceeding other unforeseen limitations (e.g., circulation, corrosion, pollutant emissions, auxiliary equipment, etc.), a comprehensive boiler performance evaluation should be performed prior to design engineering. Such a performance evaluation effort both defines the dormant capacity of the recovery boiler and provides a firm process engineering basis prior to proceeding with the design engineering effort.

## Limitations to capacity upgrade

Several factors can limit the ultimate firing capacity of a recovery boiler. Each should be considered thoroughly before designing an upgrade.

### Water wash frequency

The factor that most often determines the capacity of a recovery boiler is the unit's pluggage rate of the convective tube sections with char and smelt carryover and flyash. The increased frequency of shutting down the boiler to water wash the fire side of the tube sections when firing at higher capacities can become prohibitive. In the short term, repeated water washes can reduce the average firing capacity to lower levels; and, over the long term, the repeated outages can cause damage to various boiler components.

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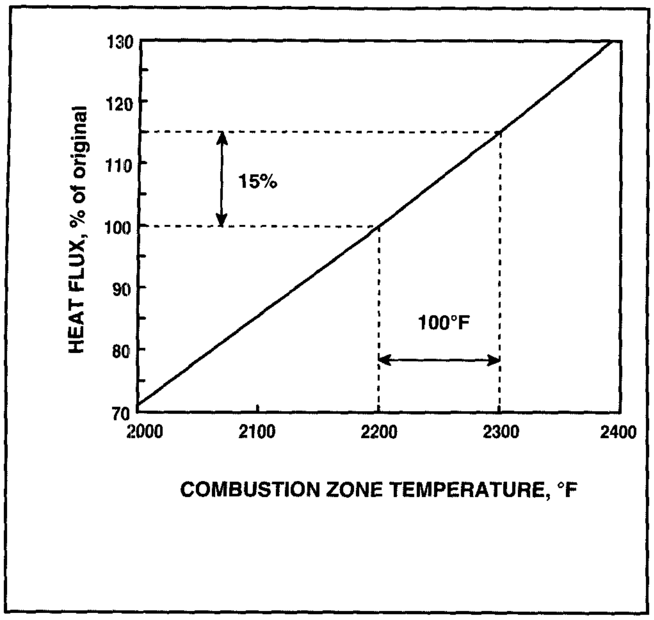
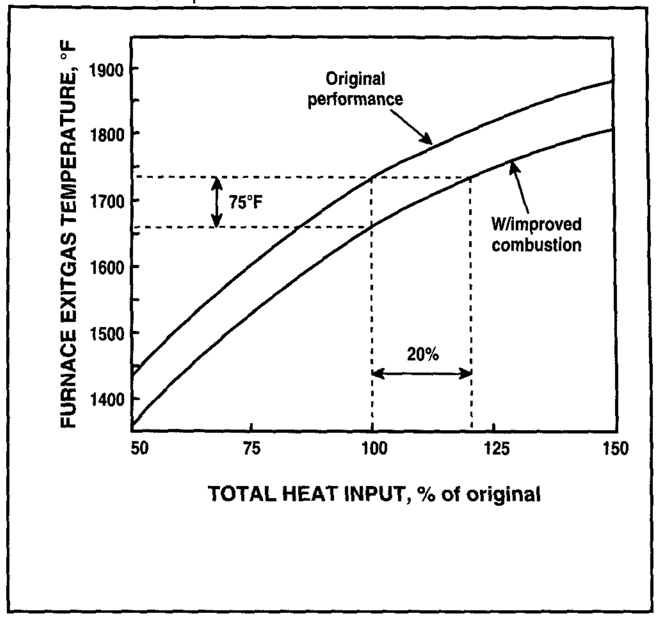
1. Example of heat flux increase at higher combustion zone temperatures




2. Relationship between heat input and furnace exit gas temperature as combustion is improved




### Corrosion rates

Overloading a recovery boiler without improving the combustion system can produce an extended combustion zone into the upper furnace and beyond into the superheater region. High heat fluxes and corrosive deposits can cause excessive superheater tube corrosion rates and steam temperature control problems *(1)*.

In some circumstances, increased firing rates can cause locally increased metal wastage of the furnace wall tubes, particularly for high-pressure boilers (above about 900 psig) with carbon steel tubes. For this reason, many recovery boilers have undergone lower furnace replacements with composite (stainless steel-clad) tubes.

### Boiler circulation

Increased steaming rates can produce conditions that cause overheating and failure of furnace wall, screen, or generating bank tubes. In the worst conditions, a water tube failure can lead to a smelt water explosion.

Increased steaming rates also place greater demands on the steam drum separating capabilities. If the firing capacity increase pushes the steam flow beyond the steam drum separating capability, carryover of water droplets from the drum can result. Poor steam quality from the steam drum can lead to scaling of superheater tubes and increased corrosion rates.

Calculation procedures and circulation monitoring equipment are available to help evaluate and measure circulation conditions in recovery boilers being considered for an upgrade *(2)*.

### Char bed control

On occasion, increased firing rates cause uncontrollable char bed growth or an unstable bed with multiple, constantly moving peaks. This situation requires constant operator attention and could lead to bed blackout conditions. Bed blackout can cause a buildup of combustible gases in the furnace and, in the worst case, can lead to a combustible gas explosion. An excessively large bed can collapse and cover the smelt spouts and primary air ports with char and smelt.

On the other hand, excessive suspension burning, associated with increases in firing rate, may lead to the complete absence of a char bed. With excessive suspension burning, the combustion zone is shifted higher in the furnace, effectively reducing the residence time available in the furnace cavity for complete burnout.

### Pollutant emissions

Increased firing rates without improved combustion can lead to poor burnout of CO and total reduced sulfur (TRS) compounds in the recovery boiler furnace. In some cases, TRS emission regulations have limited the firing capacity of recovery boilers.

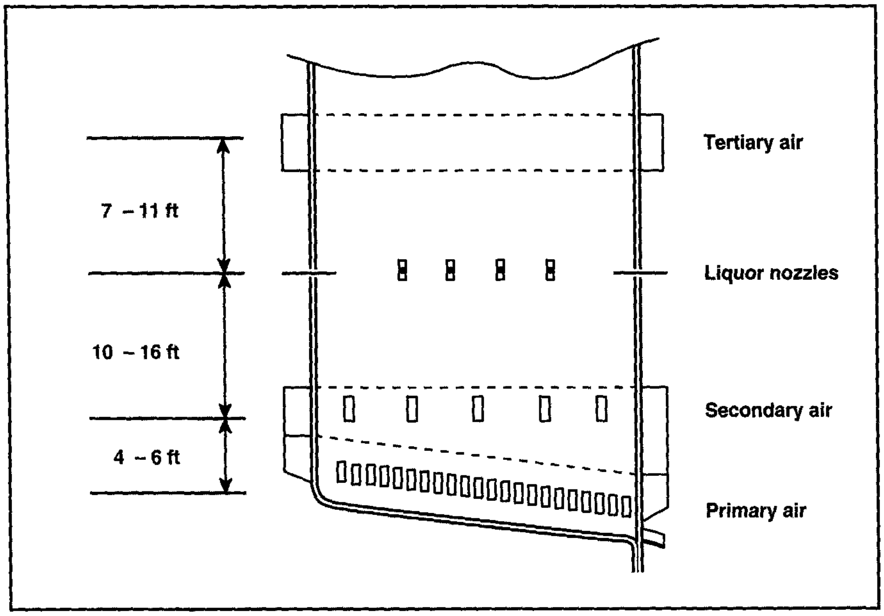
Recently, concerns over $NO_x$ emissions and impending regulatory action have raised questions about the impact of combustion system upgrades on emissions of this pollutant. As will be discussed later, limited data on the impact of combustion improvements from high solids firing have shown mixed results.

### Auxiliary equipment

Attempts to increase capacity may be limited by a boiler component or related auxiliary equipment; each should be evaluated in a boiler upgrade program. These items include:

- Induced- and forced-draft fans
- Air heaters
- Feedwater pumps

**3.** Typical air and liquor nozzle elevation ranges for a three-level air system




- Liquor pumps
- Liquor heaters
- Number, size, and type of liquor guns
- Sootblowers
- Direct-contact evaporators
- Precipitator
- Steam separators
- Steam safety valves.

Other equipment in the recovery and recaust areas—such as the multiple-effect evaporators, lime kilns, slakers, causticizers, and clarifiers—must also be evaluated to determine their capacity limitations.

## Benefits of improved combustion

Many of the recovery boiler capacity limitations previously described can be overcome by improving combustion conditions within the boiler. Typically, increased capacity can be achieved through modification of combustion system hardware without altering the convective sections of the boiler.

Better burnout of combustible material in the lower portion of the furnace cavity can reduce pluggage rates by lowering the number of char particles that are carried to the convective passes. By exposing sufficient oxygen to the fuel in an intense mixing region, the char and devolatilized gases generated from the liquor spray can be burned rapidly and completely in the lower furnace (below the highest level of air injection). It has been shown that the overall rate of the combustion process in a recovery boiler is governed not by chemical kinetics but by the rate of mass diffusion that brings the reactants together *(3)*. The improved combustion conditions also reduce CO and TRS emissions.

The higher flame temperatures in the lower furnace due to increased combustion rates cause a higher heat flux to the furnace walls. Since radiant heat flux is a function of the radiating temperature to the fourth power, small increases in combustion intensity can lead to significant increases in heat absorption in the lower furnace. Radiant heat absorption is described by the following equation:

$$E = \sigma\varepsilon_s(\varepsilon_g T_g^4 - \alpha_g T_s^4) \qquad (1)$$

where

$E$ = net heat absorbed per unit of area

$\sigma$ = Stefan-Boltzmann constant

$\varepsilon_s$ = surface emissivity

$\varepsilon_g$ = gas emissivity

$T_g$ = gas absolute temperature

$\alpha_g$ = gas absorptivity

$T_s$ = surface absolute temperature.

As shown in **Fig. 1**, for typical recovery boiler conditions, an increase of 100°F in combustion zone temperature in the lower furnace can increase heat flux to the water walls by about 10–20% in this region. The increased heat absorption results in a lower furnace exit gas temperature for the same heat input. This effect is illustrated in **Fig. 2**. Consequently, improved combustion intensity in the lower furnace allows a higher heat input rate for the same furnace exit gas temperature.

Once the maximum furnace exit gas temperature has been reached, the temperature profile throughout the convective sections is approximately the same as before the combustion improvements. This is important in that the plugging of the superheater and generating bank sections is partly a function of the local gas temperature. Higher gas temperatures can produce stickier deposits that contribute to rapid plugging of passages between tubes.

The higher bed temperatures that result from improved combustion lower the amount of sulfur driven from the bed and increase the amount of sodium fuming. Sodium fume reacts with $CO_2$ and $SO_2$ in the gas stream to form sodium carbonate and sulfate. Low $SO_2$ in the flue gas leads to low levels of $SO_3$, which is a precursor to sodium bisulfate and/or pyrosulfate formation. Sodium bisulfate and pyrosulfate are low-melting-point materials that can contribute to the flyash stickiness in the generating bank, economizer, and precipitator. They can also contribute to low-temperature corrosion.

Therefore, improved combustion in the lower furnace helps to reduce pluggage in three ways. Better burnout of char reduces the amount of material entrained with the flue gas. Flue gas temperatures can be depressed or held constant at higher firing capacities. Flue gas temperatures can be depressed or held constant at higher firing capacities. Finally, higher fuming rates promote $SO_2$ scrubbing and $SO_3$ depression, which can prevent sticking and bridging of flyash in the back end of a boiler. As mentioned earlier, improved combustion also lowers CO and TRS emissions from the boiler by burning out these species prior to the quenching action of the convective sections.

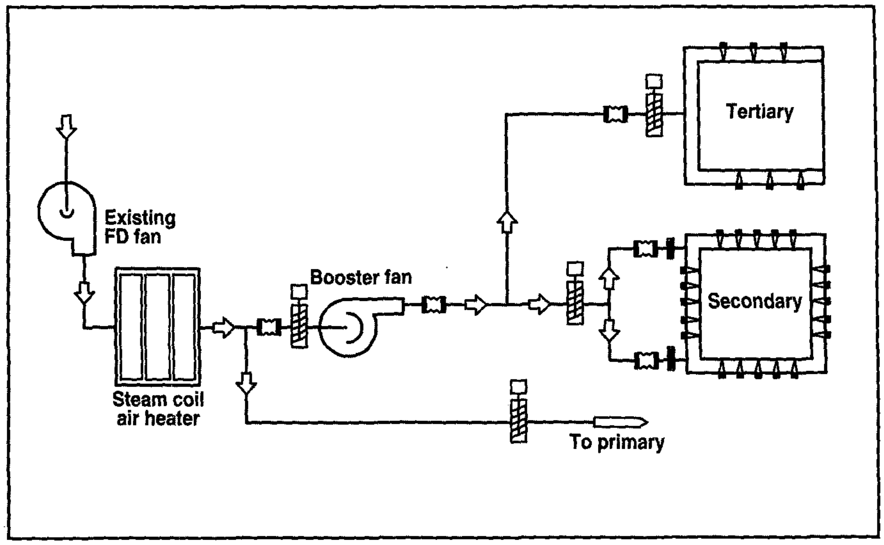
Higher bed temperatures and bed char combustion contribute to good smelt reduction efficiencies. High smelt reduction efficiencies (>92%) over time lower the dead chemical load in the white liquor. This lower dead load can result in reduced demands on evaporators, concentrators, and liquor handling equipment as boiler firing capacity is increased. Another outcome of lower dead load is a small rise in liquor heating value.

Recently, $NO_x$ emissions have been an area of keen interest, as local regulatory agencies are establishing limits for this pollutant from recovery boilers. However, the increase in combustion temperatures due to a combustion system upgrade would not be expected to significantly increase $NO_x$ emissions. The temperatures are considered to remain too low to contribute to "thermal $NO_x$" formation.

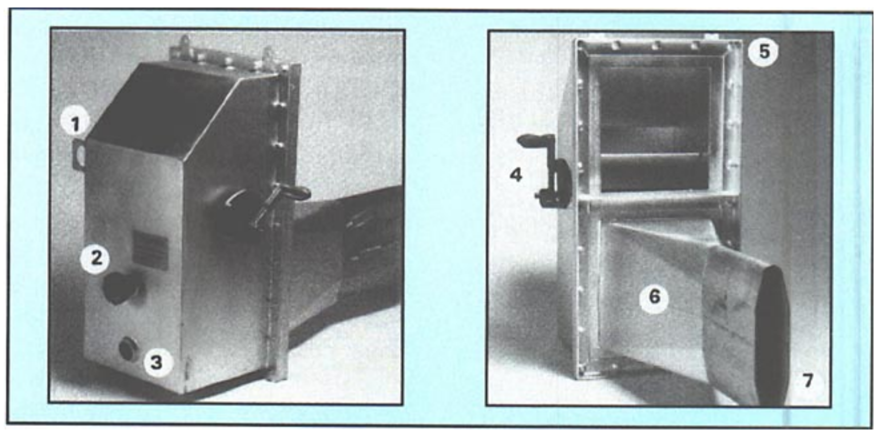
There have been conflicting results in the literature on the effect of liquor firing solids on $NO_x$ emissions *(4, 5)*. Increases in combustion temperatures due to higher solids firing have been reported to cause both a rise and a drop in $NO_x$ emissions from different recovery boilers.

One of the upgrades described later in this paper was equipped with continuous $NO_x$ monitoring equipment after the upgrade. At this mill, the $NO_x$ emissions are consistently within regulatory limits (80 ppm) regardless of firing conditions. The issue of $NO_x$ emissions from recovery boilers continues to be an active area of research and regulatory debate.

4. Example flow diagram of an air system upgrade that included a booster fan




5. High-energy combustion air nozzle design components: (1) pressure gauge bracket, (2) view port, (3) clean out port, (4) air control damper, (5) bolted windbox interface, (6) convergent section, (7) contoured nozzle discharge (stainless steel)




## How to achieve improved combustion

There are several guidelines to follow in achieving improved combustion in recovery boilers. These are outlined in the following sections.

### Sufficient air in lower furnace

For the combustible material in the liquor to burn low in the furnace, there must be sufficient oxygen present to support combustion. The air delivery system must be capable of satisfying the increased air demands at upgrade firing conditions. It should also be able to supply nearly a stoichiometric amount of air to the lower furnace. Less-than-stoichiometric air assures that significant combustible material enters the upper furnace, which is contrary to the goal of achieving increased capacity.

### Three levels of air injection

Recovery boilers, as typically designed in the past, are not equipped to deliver the large amounts of air to the lower furnace that are required for higher firing rates. Attempts to increase the amount of air in the lower furnace most often result in excessive velocities through the primary ports, which can contribute to carryover of char material into the upper furnace and lower reduction efficiencies. This is particularly true for units that are equipped with only two levels of air.

A combustion air split of approximately 40% primary, 45% secondary, and 15% tertiary, with an overall excess air level of 15%, provides a stoichiometric mixture of air and fuel to the lower furnace. The tertiary air becomes a polishing stage to burn out residual gaseous combustible material and for $O_2$ level control. Since a relatively small amount of air is used at the tertiary level, the air delivery hardware at this level must be effective to achieve good mixing conditions.

**Figure 3** presents typical elevations of the secondary air, liquor nozzles, and tertiary air levels above the primary air elevation. The location of new secondary and tertiary air levels, and the air delivery ducting and windboxes, are often impacted by structural and boiler interferences that can complicate the design.

### Deep air jet penetration at secondary and tertiary levels

In most upgrades, the primary port openings are retained, and the amount of air delivered to the primary level is determined based on injection velocities. On two-level units, a new overbed (secondary) level of air must be added. On three-level units, the secondary must be upgraded to accommodate higher flow rates and to obtain higher injection velocities.

As previously mentioned, the tertiary air level is also typically upgraded to achieve deep jet penetration and good mixing with the relatively small amount of air introduced at the tertiary level. As a consequence, conversion of tangential air delivery systems to opposed air nozzles is typically performed at the tertiary level.

**Figure 4** presents an example flow diagram of an air system upgrade that included the installation of a booster forced-draft (FD) fan. The booster fan allows reuse of the existing FD fan and steam coil air heater while meeting the high flow and pressure requirements of the secondary and tertiary air levels.

As a guideline, calculations can be performed for a single jet in a uniform cross-flow to characterize the jet penetration from an air port for differing boiler geometries and conditions. One useful correlation for jet trajectory is *(6)*:

$$z/d_o = 1/R(x/d_o)^{2.55} + x/d_o(1 + 1/R)\cot\theta \qquad (2)$$

where

$z$ = distance in the direction of the cross-flow

$d_o$ = equivalent initial jet diameter

$R$ = momentum flux ratio = $\rho_o v_o^2/\rho_f v_f^2$

$\rho_o$ = jet fluid density

$\rho_f$ = furnace fluid density

$v_o$ = initial jet velocity

$v_f$ = furnace cross-flow velocity

$x$ = distance in direction of jet injection

$\theta$ = angle between initial direction of jet and that of cross-flow.

Another useful relation is the rate of jet entrainment *(7)*:

$$m_x/m_o = 0.32(\rho_f/\rho_o)^{0.5}(x/d_o) \qquad (3)$$

where

$m_x$ = mass flow rate of entrained fluid

$m_o$ = initial mass flow rate of jet.

Although these equations do not fully describe the complex mixing and jet interaction that occur in recovery boilers, they provide fundamental relationships that allow proper sizing of air system components for boilers of different scales. This kind of approach to air system scaling helps to assure proper specification of the number of air nozzles, nozzle size, and FD fan flow and pressure requirements. A more detailed discussion of flow and mixing within recovery boilers can be found in a review by Adams and Frederick *(8)*.

### Uniform air and liquor distribution

Approaches to air introduction and distribution vary widely between boiler upgrade engineering teams. Each approach has its potential benefits and shortcomings. One approach is to achieve the most uniform air and liquor delivery possible. This requires a similar number of secondary air ports and liquor gun ports on each wall. Uniform injection of air and liquor assures uniform combustion throughout the lower furnace volume and a uniformly shaped char bed. Other approaches include various two-wall air injection schemes that attempt to reduce peak upward flue gas velocities in the center of the furnace. Most upgrade approaches feature stationary liquor firing with multiple nozzles in service.

### Control of airflow distribution

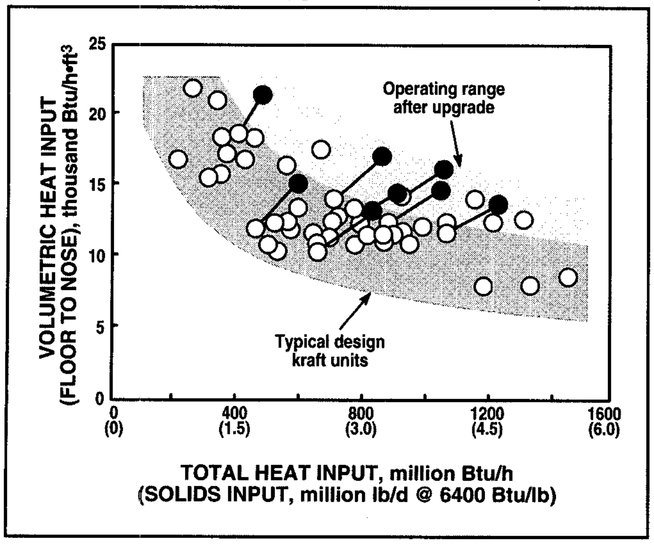
**Figure 5** presents photographs of a patented air nozzle design *(9)*. Airflow uniformity through the secondary and tertiary nozzles is achieved with butterfly dampers and pressure gauges on each nozzle. With these tools, each nozzle can be balanced to achieve the desired flow rate; individual nozzles can be turned off. In the case of reduced boiler load, it is recommended that a proportional number of the nozzles be turned off to maintain good jet penetration and mixing with the nozzles that remain in service.

The inlet to the air nozzles is large enough that the velocities at the nozzle entrance and across the flow control damper are low. The air is then gradually accelerated in a convergent section to the desired furnace inlet velocity. This approach minimizes the energy dispersion and pressure drop across the nozzle/damper assembly and contributes to better windbox airflow distribution. Consequently, less FD fan pressure is required to achieve the desired airflow results.

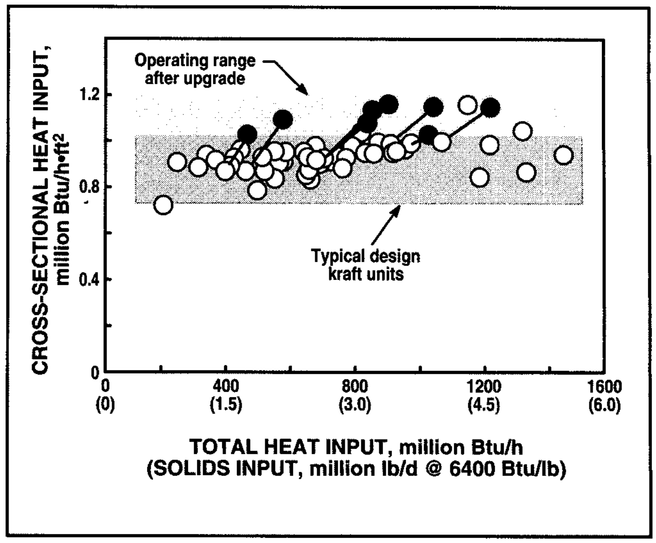
### Directional control of liquor sprays

Stationary liquor firing, using a relatively large number of splash plate-type nozzles, is typically recommended to distribute the liquor well over the char bed without spraying it on opposing and adjacent furnace walls. This approach also minimizes liquor spray

6. Comparison of design vs. upgraded volumetric heat input rates




7. Comparison of design vs. upgraded cross-sectional heat input rates




into the upper furnace by avoiding regions of high flue gas velocity. Lower carryover can be achieved by choosing the proper liquor gun size and liquor firing conditions (i.e., pressure and temperature), and by aiming the liquor spray more directly toward the char bed. The more direct injection usually requires steadier liquor conditions than previously required. In particular, an indirect liquor heater may be required to achieve the desired level of liquor temperature control.

I. Recovery boiler upgrade summary

| | | *Design* | *Pre-upgrade* | | *Upgrade* | |
|---|---|---|---|---|---|---|
| *Unit* | *Manufacturer* | *Solids, million lb/d* | *Heat input, % of design* | *Solids, million lb/d* | *Heat input, % of design* | *Solids, million lb/d* |
| A | CE | 3.6 | 95 | 3.9 | 108 | 4.4 |
| B | B&W | 3.3 | 93 | 3.1 | 118 | 3.9 |
| C | B&W | 2.4 | 109 | 2.6 | 125 | 3.0 |
| D | B&W | 2.4 | 108 | 2.6 | 129 | 3.0 |
| E | CE | 3.0 | 103 | 3.3 | 119 | 3.8 |
| F | B&W | 1.8 | 109 | 1.5 | 125 | 2.3 |
| G | CE | 2.6 | 107 | 2.8 | 121 | 3.2 |
| H | B&W | 1.4 | 103 | 1.6 | 116 | 1.8 |

## Performance results

A large number of recovery boilers have been upgraded over the last few years. One means of comparing performance between boilers and characterizing the upgrade potential of boilers is a cumulative plot of total heat input vs. geometric parameters. **Figures 6 and 7** present plots of the design conditions for over 40 boilers. On both a volumetric and cross-sectional heat input basis, combustion improvements have been successful in establishing a new standard of performance. Eight of these boilers have achieved increases in heat input ranging from 13% to 25% above the pre-upgrade level. Considering the difference in design virgin liquor heating value (typically 6400–6700 Btu/lb) to actual virgin liquor heating values (typically 5700–6200 Btu/lb), these units have seen even greater percentage increases in solids firing rates over the design rates (18% to 29%).

Pluggage rates in the convective sections of the upgraded units have varied from one water wash per year to not more than four. Economizer pluggage has also been reduced due to the increased fuming rates in the lower furnace, producing less sticky ash deposits.

Now that a sufficient number of units have been upgraded to firmly establish a potential operating range, the information contained in Figs. 6 and 7 can be used in conjunction with a boiler performance evaluation to determine the dormant capacity of a recovery boiler.

**Table I** provides comparisons of design, pre-upgrade, and post-upgrade operating conditions on Babcock & Wilcox (B&W) and Combustion Engineering (CE) recovery boilers. More detailed descriptions of recovery boiler upgrades can be found in the literature (*10–13*).

## Summary

Recovery boiler firing capacity is often the bottleneck that prevents increased pulp production. Several elements can limit the firing capacity of a recovery boiler, including liquor combustion, steam generation, and auxiliary equipment-related factors. Each should be fully evaluated before proceeding with an upgrade.

Improvements in liquor combustion offer several benefits that can improve boiler performance and allow increased firing rates without the need for pressure part modifications of the convective sections. More intense combustion in the lower furnace reduces carryover of char material into the upper furnace, reduces furnace exit flue gas temperatures, and improves bed controllability and smelt reduction efficiency.

Improved combustion is achieved by redistributing the combustion air throughout the boiler, concentrating more air in the lower furnace. Intense mixing can be achieved through the use of patented high-energy combustion air nozzles at the secondary and tertiary levels. Butterfly dampers and pressure gauges on these nozzles allow individual flow control, so flow uniformity can be achieved through all nozzles. In combination with air delivery improvements, the liquor spray delivery must also typically be improved to provide uniform distribution and to avoid spraying fine droplets into high-velocity regions.

Several successful recovery boiler upgrades have established new performance standards, which can be used to identify the dormant capacity of other units. Increases in heat input to the recovery boilers and in solids firing rates have been as much as 25% over design and pre-upgrade levels. Concurrently, water wash frequencies have been kept to acceptable levels, and TRS emission levels have been in compliance with regulatory limits. Proper boiler evaluation and hardware improvements to enhance liquor combustion offer many mills the opportunity to increase profits within one year. TJ

## Literature cited


1. La Fond, J. F., Verloop, A., and Walsh, A. R., *Tappi J.* 75(6): 101(1992).
2. Sonnichsen, T. W., Walsh, A. R., and Elliott, J. S., *CPPA 1991 Annual Meeting Notes,* Technical Section, CPPA, Montreal, p. A161.
3. Brown, C. A., Grace, T. M., Lien, S. J., *et al., Tappi J.* (72)10: 175(1989).
4. Jones, A. K. and Stewart, R. I., *TAPPI 1992 International Chemical Recovery Conference Proceedings,* TAPPI PRESS, Atlanta, p. 365.
5. Hyöty, P. and Mäntyniemi, J., *TAPPI 1992 International Chemical Recovery Conference Proceedings,* TAPPI PRESS, Atlanta, p. 405.
6. Abramovich, G. N., *The Theory of Turbulent Jets,* (Translation by Scripta Technica, L. H. Schindel, Ed.), M.I.T. Press, Cambridge, MA, 1963.
7. Ricou, F. P. and Spalding, D. B., *Journal of Fluid Mechanics* (11): 21(1961).
8. Adams, T. N. and Frederick, W. J., *Kraft Recovery Boiler Physical and Chemical Processes,* The American Paper Institute, New York, 1988, pp. 149-170.
9. Jansen, J. H., U.S. pat. 4,940,004 (July 10, 1990).
10. Verloop, A., Jansen, J. H., and Danroth, D. E., *Pulp Paper Can.* (91)4: T141(1990).
11. Verloop, A., Sonnichsen, T. W., and Jansen, J. H., *TAPPI 1988 Engineering Conference Proceedings,* TAPPI PRESS, Atlanta, p. 369.
12. Verloop, A., Sonnichsen, T. W., and Strandell, O., *Tappi J.* (73)3: 145(1990).
13. Harsent, B., Elliott, J. S., and Sonnichsen, T. W., The Mackenzie Recovery Boiler Upgrade, paper presented at the Canadian Pulp and Paper Association 1990 Spring Conference, Jasper, AB, Canada, May 17-19, 1990.



Received for review July 10, 1992.

Accepted April 12, 1993.

Presented at the TAPPI 1992 Engineering Conference.