A RELIABLE HIGH EFFICIENCY SUGAR MILL BOILER

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Abstract

A new 150 tph dual fuel (bagasse/coal) boiler was commissioned in early 1984 at Tongaat-Hulett Sugar's Maidstone mill. Continuous operation for nine to ten months of the year and substantial energy exports (as bagasse, steam and electricity) from this factory led to the incorporation in the new boiler of a number of novel features likely to have application elsewhere. The paper describes the evolution of the boiler design to meet the requirements of high availability and high thermal efficiency, with particular reference to the unique main bank and heat recovery equipment. Experience of its first season of operation is related.

The Maidstone Sugar Mill

Increases in factory steam demand, deterioration of two old boilers to the stage where they would have required major repairs and the opportunity to effect substantial labour and fuel savings prompted the decision in early 1982 to order a new boiler for Tongaat-Hulett Sugar's Maidstone mill. This boiler was commissioned early in June 1984.

Features of the Maidstone mill which had direct bearing on the boiler requirements included:

- The mill runs continuously for approximately nine months of the year (11 months in 1984-85), stopping only one of its two extraction plants each week for maintenance.
- Mill cane supplies are characterised by high fibre (generally 16 to 17% on cane) though weekly figures of below 14% are occasionally recorded (e.g. after large fires). Bagasse moistures are unusually high and variable, particularly from the diffuser extraction plant where dewatering is by a single mill (weekly moisture % bagasse figures range from 51 to 57%).
- The mill provides large "energy" exports, in the form of bagasse (10 to 25 tph), steam (10 to 20 tph) and electricity (4 to 8 MW).

These circumstances resulted in the mill energy balance varying from a deficit with more than R750 000 per annum of coal burning to a surplus requiring R250 000 per annum bagasse dumping costs.

Requirements For The New Boiler

Because of these features of the Maidstone mill, more than usual emphasis was placed during the tender adjudication and design negotiations on three criteria: thermal efficiency, reliability/availability and operating requirements.

(1) *Thermal Efficiency*

Supplementary coal burning costs were already high and likely to become of even greater concern because of higher imbibition rates, hoped-for reductions in fibre % cane from more burnt cane and possible increases in energy exports.

On the other hand, bagasse dumping was both costly and environmentally undesirable (dust nuisance, fire hazard and unsightly) and suitable land for dumping was becoming scarce.

Factory heat balance calculations showed that the highest economically feasible thermal efficiency would not entirely eliminate coal burning during the winter months but, in order to avoid excessive bagasse disposal costs in warmer and high fibre periods, it would also at times be necessary to operate in a low efficiency or "incineration" mode.

(2) *Reliability and Availability*

The new boiler would be "front-line" equipment in that two old w.i.f. boilers which were in poor repair, labour-intensive and inefficient, were to be scrapped, so that full factory throughput would not be maintainable without at least part load from the new boiler.

The continuous factory operation and the export power commitments further dictated that the new boiler should have a high reliability and a high availability (able to steam continuously for up to six months without a maintenance stop). It was necessary to be able to maintain steam on coal in the event of bagasse supply failures.

(3) *Operating Requirements*

Operation would need to be by relatively unsophisticated sugar mill boiler staff but nevertheless sufficiently automated to minimise staff and maximise reliability.

The impact of these three requirements on the selection and design of the boiler is discussed.

Boiler Size and Supplier

The factory's steam and energy balance and the scrapping of two old boilers required that the new boiler be of at least 120 tons steam per hour capacity on bagasse fuel. However, a 150 tph boiler would permit another old boiler to be taken off line to provide labour and maintenance savings and improved overall boiler house thermal efficiency. Tenders showed that the additional 25% capacity of the larger unit would in this instance only increase the overall project cost by just over 10%. This additional cost was justified by the labour and fuel savings and the larger unit was therefore decided upon. Coal-fired capacity was quoted in all tenders at approximately 80% of that on bagasse, due to the constraint that the grate heat release rate was to be limited to approximately 1 700 kW/m^2 on coal.

Only well-established suppliers with proven experience of bagasse-fired boilers under South African conditions and with competent local technical and service support were considered. Of these, John Thompson Africa (Pty) Limited, were awarded the contract.

Fuel Feeders

The reliability/availability requirement determined a preference for separate bagasse and coal feeders and distributors.

Consideration was given to bagasse drying (using boiler flue gases) with direct pneumatic feeding from the bagasse drier. Although this option could potentially provide the highest thermal efficiency, the extra overall system efficiency (after allowing for additional power requirements) of at most 1 to 3% over the design chosen could not justify the additional capital cost and maintenance requirements and was also offset by the potential downtime from additional equipment needed with this relatively little tried technique. These conclusions have subsequently been confirmed by the studies of authors such as Keensliside[2] and Joshi and Vaidya[1]; bagasse drying is not usually the best efficiency option for a sugar mill.

Convection Bank - Single-pass or 3-pass?

Transverse baffle maintenance, which had been a problem in early 3-pass designs, was no longer regarded as a major problem with modern baffle construction techniques, but 3-pass boilers in the South African sugar industry had in recent years acquired a bad reputation amongst engineers for main bank tube failures as a result of external erosion from heavy sand and fly ash loadings carried over with the furnace gases. This erosion occurred most seriously in the areas of turbulence where gas flows were reversed around the tips of baffles, a phenomenon described and explained by Magasiner *et al*[5]. In single-pass designs, the lower velocities across the main bank and absence of direction changes obviated these problems. This was an important consideration for this boiler in view of the reliability requirements.

However, the Maidstone requirement for maximum thermal efficiency resulted in a significant cost differential in favour of the 3-pass unit. The main tube bank provides relatively the cheapest heat recovery surface in a boiler and in a 3-pass design the gas temperature leaving the main bank will be of the order of 340°C as compared to a value of 375°C which can economically be obtained after a single-pass main bank. Single-pass high efficiency designs consequently require large, costly heat recovery units (economisers and airheaters) at the rear of the boiler, which in this instance resulted in the cost of a single-pass boiler for the required efficiency being 3 to 5% higher than that of a 3-pass unit.

The additional heat recovery equipment required on a single-pass boiler also resulted in a taller or deeper design which presented accommodation problems in the preferred factory location.

A further study was therefore undertaken of the 3-pass erosion problems to determine whether these could be either eliminated completely or protected against. Useful information was obtained from studies such as those of Magasiner[4] and of Levy and Frost[3] and the main findings of Moir and Mason[6] were by this time also known. But more specific detail was wanted.

Fortuitously, a 3-pass John Thompson boiler at Amatikulu was experiencing serious main bank tube failures at the time. A number of failed tubes had been blanked off and the entire main bank was about to be replaced. This provided an opportunity to examine thoroughly the normally inaccessible areas in the middle of the bank where this erosion occurred. On stripping the bank, it was found that the erosion was severe but extremely localised — typical of the effect subsequently described by Magasiner *et al*[5]. Wear was confined entirely to approximately 150 mm of the first row of tubes opposite the end of the top baffle and to approximately 100 mm of the tubes in the following row (Figure 1). While the tubes in this area had been eroded deeply — to failure in many cases — the remainder of the main bank was entirely free of erosion and was in fact covered externally with a light deposit of scale and dust.

No erosion could be observed or measured at the tip of the lower baffle although there was no external deposit on the tubes in this area indicating near-erosive conditions.

This same boiler had previously suffered severe erosion in the back row of its superheater tubes and on the bends at the outer ends of the drainable superheater, with the result that the superheater had been renewed two years previously. On renewal, the design had been slightly modified to eliminate the back row of tubes which had been most seriously eroded. Protective shields had been installed over the vulnerable bends.

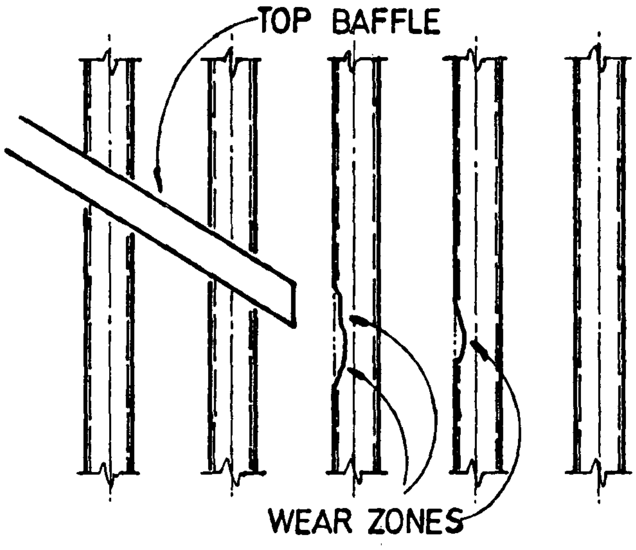


FIGURE 1 Tube Erosion Area in Main Bank

Examination of this superheater after two seasons showed no tube erosion whatsoever although the shields over the bends had suffered some wear.

The experience with this Amatikulu superheater and the extremely localised zone of erosion in the main bank suggested a simple solution to the problem — eliminate all tubes from the erosion zones. This was achieved by extending the lower baffle through to the back of the main bank and by providing a gap approximately 400 mm wide through the centre of the main bank corresponding to the end of the upper baffle, as shown in the boiler cross-section (Figure 2). The 400 mm gap in the bank not only eliminates a wear area, but also provides useful access for inspection and maintenance.

It was hoped and expected that these measures would completely eliminate the erosion problem, but two further low-cost precautionary measures were adopted in case any tendency to wear remained:

- Flue gas velocities were limited to a maximum of 15 m/sec at any cross-section.
- The entire main bank was ordered of 3,66 mm wall thickness instead of the 3,25 mm wall normally specified. As the thickness required to withstand 3 100 kPa internal pressure is approximately 0,9 mm, this increases the potential wear/corrosion allowance from 2,35 to 2,76 mm, or by 17%.

The additional cost of the 400 mm gap and thicker walled tubes was less than R15 000.

Inspection at the end of the first nine months operation revealed some areas where the main bank tubes were "polished" clean of any external deposits, but there was no evidence of any measurable metal erosion. The measures adopted therefore appear thus far to have been successful.

Boiler Furnace

Alternative furnace constructions considered were welded wall, open pitched tube and tile and "sandwich wall" (see Figure 3).

Operational reliability decided the choice of tube and tile. Although welded walls are perhaps mechanically the most reliable with minimal maintenance under normal circumstances, the rapid heat sink which they provide can present problems in establishing coal ignition in the event of a sudden bagasse supply failure, with costly consequences if electricity exports

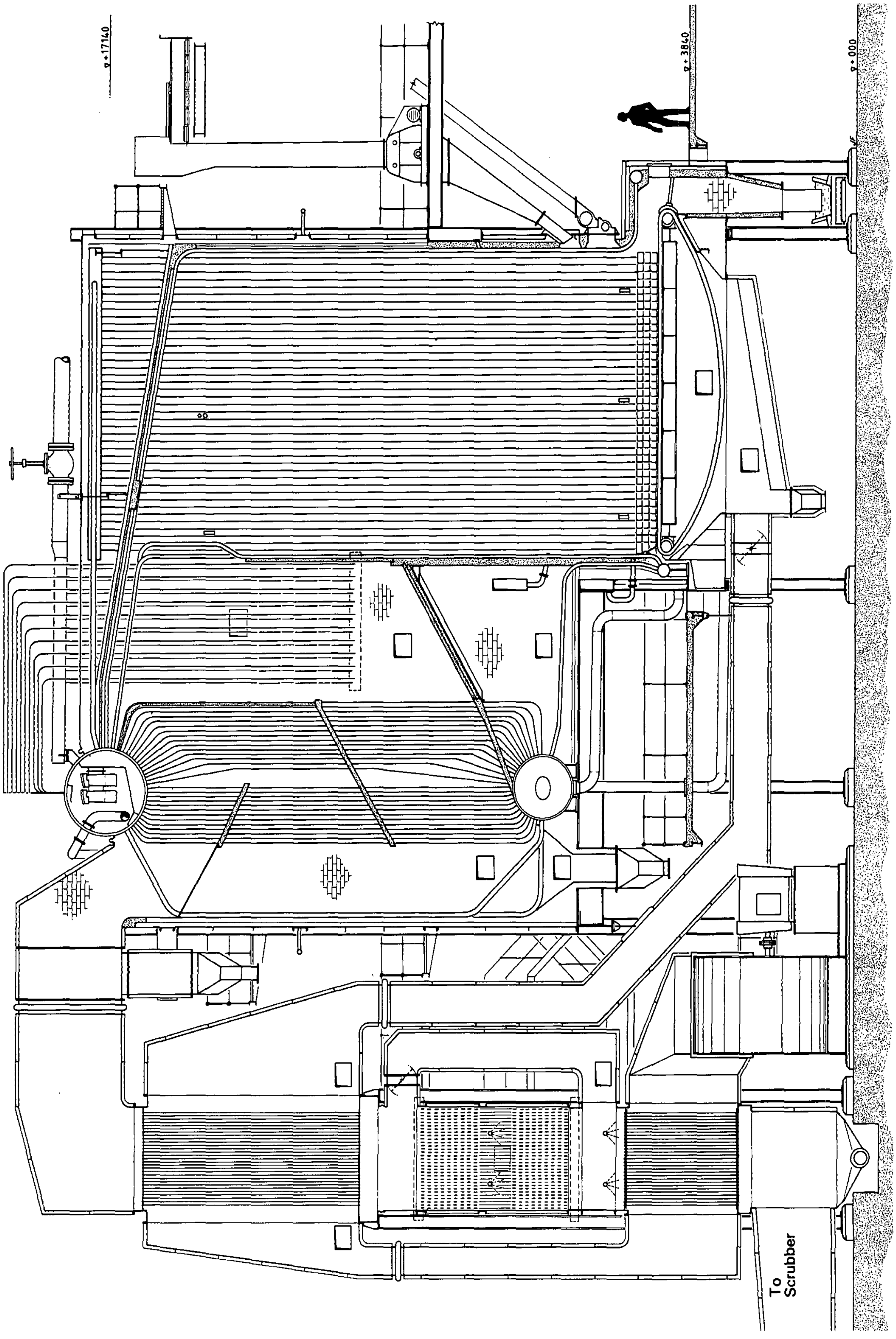
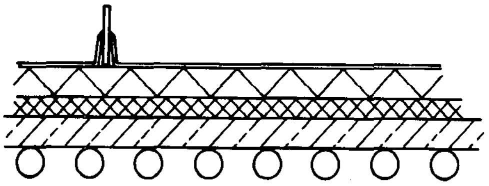
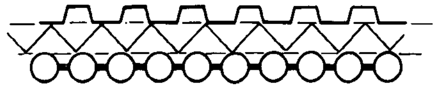


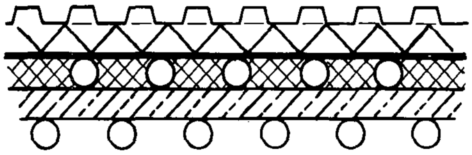
FIGURE 2 General Arrangement of the Maidstone 150-ton Boiler



Open Pitch Tube and Tile Wall



Welded (Panel) Wall



"Sandwich" Wall

FIGURE 3 Alternative Furnace Wall Constructions

are interrupted. This problem can be countered by applying a 2 to 5 m high band of gunited refractory to the lower furnace walls but this negates much of the low maintenance advantage of this construction.

The heat reserve provided by tiles helps establish the coal fire on changing fuel and reduces the dip in steam generation. It also helps to stabilise combustion with moist bagasse, thereby reducing water level excursions. Both the tube and tile and sandwich constructions provide this benefit but the sandwich construction was still unproven whereas tube and tile would be common with Maidstone's other large boiler.

The tube and tile walls have proved effective in maintaining good combustion even on high moisture bagasse and required no maintenance at the end of the first season.

Steam Drum

The nature of bagasse combustion, particularly at moistures such as experienced at the Maidstone factory, and the load fluctuations typical of a sugar mill, make the maintenance of a steady drum water level extremely difficult, even with 3-element controls. Frequent low or high water level trip-outs are consequently a common hazard with modern boilers in sugar mills. To alleviate this problem, a 1 900 mm inside diameter top drum (as opposed to the normal 1 200 to 1 500 mm diameter) was ordered. The extra cost of the larger drum proved less than anticipated — less than R30 000. The reason for this was that the wider pitching of the tube entries to the larger drum circumference increased the ligament efficiency to the extent that the same drum wall thickness could be used for the 1 900 mm ID drum as for a 1 600 mm ID drum.

The larger diameter drum had multiple beneficial effects on water level control:

- the larger water surface reduced the level fluctuation for a given change in total boiler "water" volume
- the gap between high (+470 mm) and low (−630 mm) cut-outs could be increased by slightly more than the total increase in diameter and the displacement volume between cut-outs was more than doubled
- surface turbulence was reduced by the lower steam release rate per unit area, and
- the large cross-section reduced the potential for differential levels across the width of the boiler (the "standing wave" effect).

These expectations from the larger drum have been borne out by experience in the first year of operation. This boiler is exceptionally tolerant of the type of load and firing disturbances experienced at the Maidstone Sugar mill. Two typical sections of water level control chart from the boiler (Figure 4) indicate how the conventional 3-element control maintained levels well within the wide trip-out limits, even under the most demanding conditions.

The first chart depicts a period of reasonably steady operation followed by a disturbance culminating in the other large boiler tripping out and this boiler responding with a load surge from 115 tph to 195 tph — an abrupt 70% increase in load. Water level rose to a peak of 250 mm above drum centre, using only 53% of the permissible +470 mm.

The second chart shows the effect of a total fuel supply failure, with bagasse conveyors tripping and no coal in this boiler's bunkers. Steaming rate fell to zero but water level dropped to only 220 mm of the available 630 mm range below drum centre, rising to approximately 160 mm of the available 470 mm range when load was rapidly regained.

The large steam drum decision was vindicated by the perhaps unique record for a modern sugar mill boiler of not one boiler-induced high or low-level trip out during the first nine months of operation.

Superheater

The main requirements of the superheater were good steam temperature characteristics, with preferably not more than +20°C to −20°C variation from the rated 400°C MCR temperature between 50 and 100% MCR when firing bagasse or coal, and reliability. A previous major boiler loss at Maidstone had been attributed to initial failure from overheating of a non-drainable superheater tube during firing-up and this experience led to a strong preference for a fully drainable superheater design. Another reliability concern was susceptibility to external erosion.

All these requirements were met by the horizontal cross-flow Amatikulu superheater referred to above, as modified to eliminate tubes from the high erosion zone. This design was therefore decided upon.

Two further precautions opted for were a temperature-operated automatic superheater drain valve to provide extra steam flow for tube metal cooling at low loads (cost approximately R6 000) and superheater tube wall thickness increased from 3,66 to 4,06 mm (also R6 000).

Inspection at the end of the first season revealed external polishing but no apparent erosion of the two rearmost rows of superheater tubes. The remaining tubes were all covered by light external deposits, indicating no tendency to wear.

Heat Recovery Equipment

Perhaps the most novel area of this boiler, and certainly the area which involved the most investigation, was the heat recovery equipment.

"High efficiency" bagasse/coal boilers (with both an airheater and an economiser) in South Africa have been typically designed to achieve efficiencies on NCV of the order of 83,5% on 52% moist bagasse (with a flue gas temperature of 200°C) and 86% on coal (flue gas temperature 180°C).

These efficiency limits in traditional designs were set by:

(1) The need for hot forced draught air (minimum 150°C but preferably more than 200°C) in order to satisfactorily burn

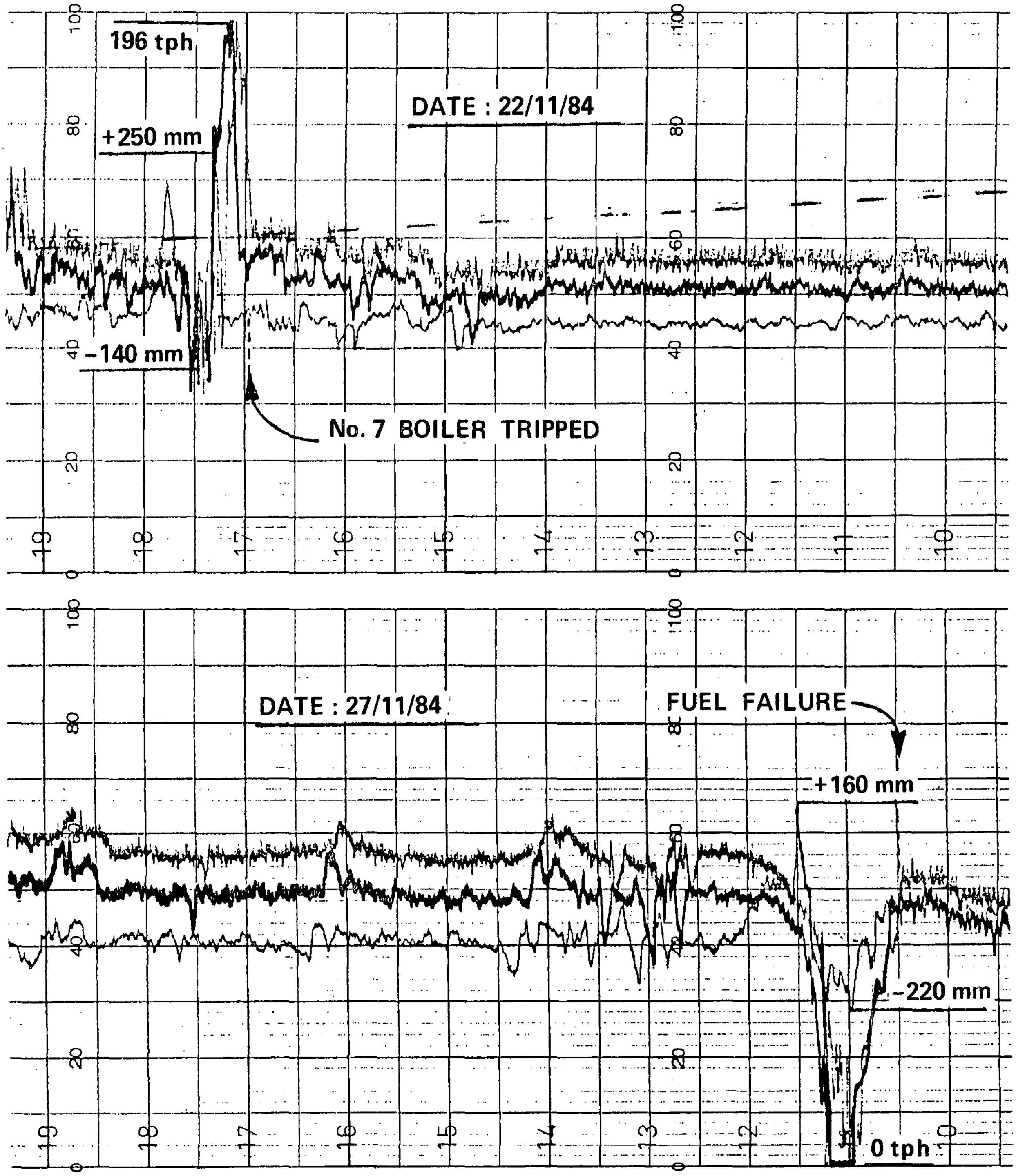


FIGURE 4 Drum Water Level Control
Scales: 0 to 200 tph steam and water flows (water offset +12 tph)
−500 to +500 mm water level from drum centre

bagasse with moistures of 50 to 55%. This required that the airheater, with its low gas-to-gas heat transfer rates, be situated upstream of the economiser.

(2) The economic limit of approach temperatures between final flue gas and hot de-aerated feedwater to the economiser.

(3) The further limitations of severe corrosion below the acid dew point in coal flue gases and of fouling with low temperature, high moisture bagasse flue gases.

Because the metal temperature in an economiser approaches that of the water rather than that of the gas, these latter two constraints are compounded: the most cost efficient economiser should incorporate counterflow heat exchanging, but this exposes the coldest tubes to the coldest flue gases, maximising corrosion and fouling potential. After extensive investigations and enquiries by John Thompson engineers into matters such as water and acid dew points in flue gases of various compositions, corrosivity of these, corrosion resistance of various materials in the projected environments, causes of fouling and techniques to prevent fouling, John Thompson and mill management finally agreed upon a unique heat recovery configuration which, at an additional cost of approximately R300 000, would achieve final gas temperatures of approximately 130°C at NER (= 0,8 MCR) on 55% moist bagasse and 122°C at NER on coal. These temperatures translated into efficiencies on NCV of:

87,4% on 55% moist bagasse with 14,2% CO_2 in flue gas, and 90,1% on coal (Zimbutu mixed smalls) with 12,7% CO_2 in gas.

Unusual features of the heat recovery equipment to achieve these efficiencies of some 5 to 6% higher than usually attainable were:

(1) Two-stage airheating, configured counterflow with the hot airheater upstream of the economiser and the cold airheater downstream of the economiser (see Figure 2).

(2) Both airheaters of vertical unfinned tubes with flue gas flow down through the tubes.

(3) The tubes of the cold airheater of type 430 stainless steel (because of its resistance to both sulphur acids and to chlorides, and after many contradictory "expert" opinions obtained).

(4) The cold airheater tube plates of "double skin" mild steel construction (see Figure 5), with the tubes expanded into the outer tube plates. The inner tube plates would be in contact with the air only, so would be cold but not exposed to flue gas acids. The outer tube plates would be exposed to the flue gases, but would approach flue gas temperature because of their air-gap insulation from the cold air.

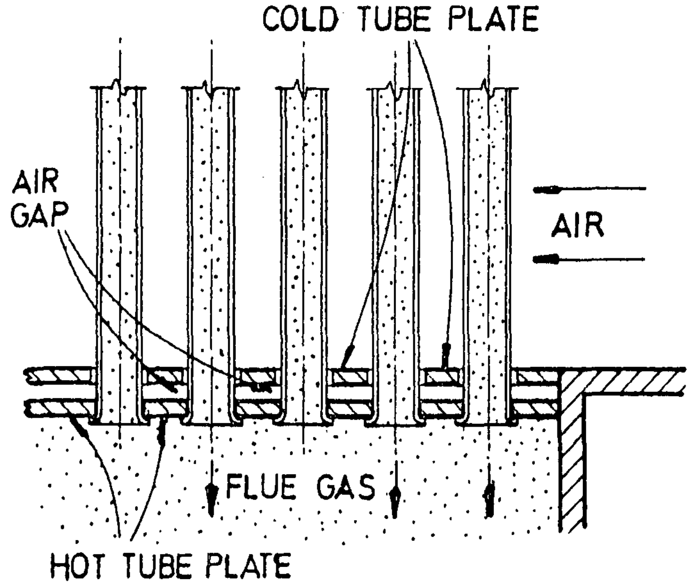


FIGURE 5 "Double Skin" Tube Plates of Cold Airheater

(5) Airheater air-side partial bypass system, to provide metal protection during start-up or low load operation.

(6) The economiser of unfinned horizontal mild steel tubes, square pitched to minimise fouling and of heavier than usual gauge to tolerate some erosion if experienced.

(7) In-line water washing sprays on the flue gas side of both the square pitched economiser tubes and the stainless steel cold airheater tubes.

(8) Economiser gas-side bypass to enable low-efficiency (incineration mode) operation in periods of bagasse surpluses.

These features have all satisfactorily served their purposes during the boiler's first nine month season. Gas exit temperatures recorded have generally been 5 to 10°C below design, giving efficiencies of 0,4 to 0,8 units higher than design. The gas-side surfaces of the lower (cold) airheater were kept 98% free of fouling for the last five months of the season by the use of the water-washing facility for 10 minutes each shift. Approximately 2% of tubes were internally fouled, but these were confined to two small areas and were probably due to blocked spray nozzles. No significant corrosion of tubes or tube plates was apparent. It was not found necessary to use the water-washing facility on the economiser.

Flue Gas Scrubber

A perforated plate-type wet scrubber of Tongaat-Hulett Sugar design was decided upon, as this design permits good turndown ratios with relatively low pressure drop and can operate continuously for months on end without maintenance stops. The average pressure drop across the scrubber at MCR on bagasse was recorded at approximately 900 Pa and the scrubber operated continuously for the last five months of the season without any maintenance or cleaning.

Induced Draught Fans

Past experience had shown that wet fans (i.e. after the scrubber) operate reliably provided droplet elimination from the gases after scrubbing is efficient. Advantages of wet fans over hot fans include the smaller (cold) volumes to displace, freedom from particulate erosion of the runner and a clean environment (all "dirty" ducts are under suction, so any leaks are inward). These decided the choice of wet fans.

Three unusual features of the induced draught fans were:

(1) Twin fans were used, both fans being required for maximum continuous rating, but each alone able to provide approximately 75% of MCR. This enables individual fan or fan drive maintenance without interruption to crushing or factory operations. Low load operation (such as on start-up or during steam trials) is also more economical on one fan.

(2) Variable speed direct current motors were selected for the ID fan drives. These provided the variable speed benefits of soft starts, mechanical efficiency and controllability at less cost and more satisfactorily than conventional fluid couplings, electro-magnetic couplings or reasonably efficient turbine drives.

A problem with the DC drive electronics caused an ID fan trip-out eight days after initial commissioning. Although no further boiler outages were caused by the ID fans, the cheaper but less flexible option of fixed speed AC electric drives with inlet vane control may have been inherently more reliable.

(3) The fans and stack were mounted on top of the concrete scrubber, conveniently accessible from the firing floor. This minimised ducting, civil works and floor area and considerably shortened the stack (see Figure 6).

Instrumentation

The control philosophy is generally conventional, but use was made of microprocessor-based configurable single loop programmable controllers. This considerably reduced the quantity of hardware required in the control room and reduced maintenance and calibration requirements.

Steam demand calls induced draught; measured air flow calls fuel via air/fuel ratio control; and furnace pressure calls forced draught. The fuel/air ratio control is trimmed by the O_2 in flue gas, as measured by a Zirconium probe, with separate settings for bagasse firing (4% O_2, wet basis) and coal firing (8% O_2). This has proved a valuable aid to maintaining efficient combustion conditions. A section of the O_2 chart shown in Figure 7 illustrates the effective control achieved even with as variable a fuel as bagasse. Control on coal is as good or better.

The water level signal to the 3-element drum level control is the average of the levels measured at each end of the steam drum. The large diameter of this drum permits an exceptionally wide level control range of 1 100 mm (+470 mm to −630 mm from drum centre line). A typical drum level chart, showing also feedwater and steam flows, is given in Figure 4.

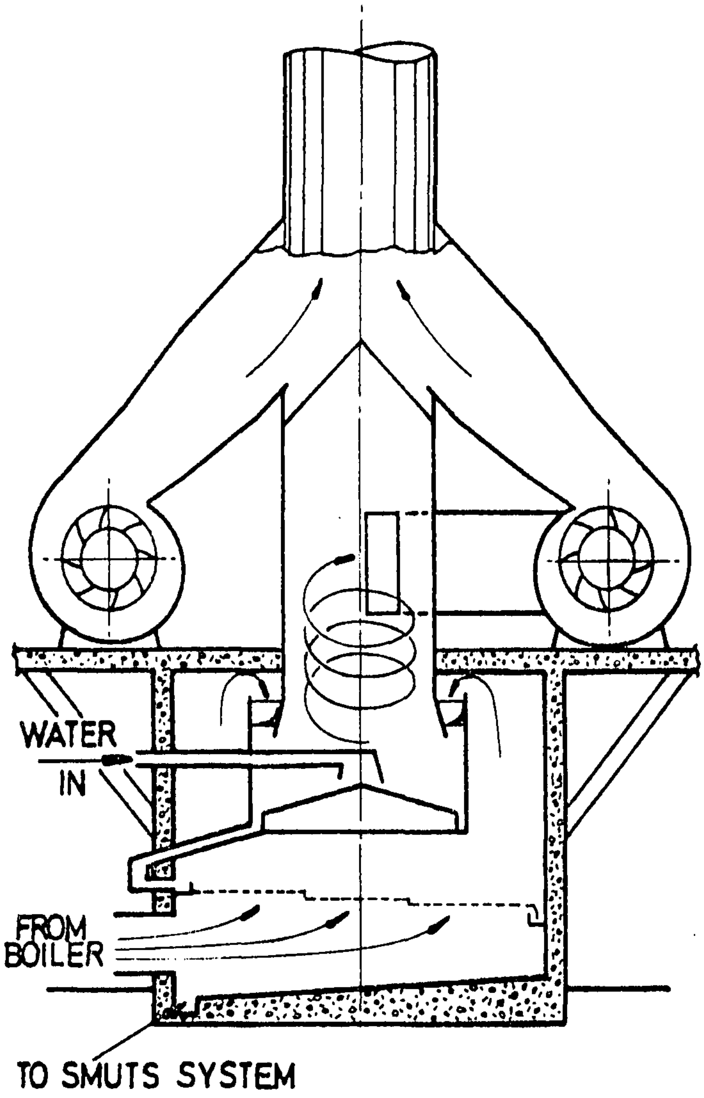


FIGURE 6 Scrubber, Fans and Stack Arrangement

Performance Schedule

The principal design performance figures for the boiler of relevance to this paper are:

Fuel	55% Moist bagasse	55% Moist bagasse	50% Moist bagasse	Coal
Operating Mode	Normal	Incinerating	Normal	Normal
Max. Continuous Rating (MCR) (Tons hr $^{-1}$)	150*	135	176	128*
Efficiency on NCV at MCR	86,2	77 ,7	87,1	89,8
at 0,8 MCR (= NER)	87,4*	78,9	88,5	90,1
at 0,5 MCR	87,6	78,5	87,9	90,0
Final gas temp				
at MCR (°C)	150	255	160	125
at NER (°C)	130	235	140	122
at 0,5 MCR (°C)	115	220	127	118
Exit steam temp				
at MCR (°C)	410	425	402	386
at NER (°C)	405*	423	398	382
at 0,5 MCR (°C)	390	415	390	372

* Guaranteed performance figures

In practice, final gas temperatures some 10°C lower than design are achieved. The Zirconium O_2 trim also enables bagasse combustion with 30 to 35% excess air (compared to 40% design) and the combined effect of these two factors results in actual efficiencies of approximately a unit higher than design.

First Season's Operations

The boiler could not be commissioned as originally planned in December 1983 due to the drought-curtailed milling season. Internal inspection in April 1984 revealed considerable deposits from poor quality storage water and the need to reclean delayed commissioning.

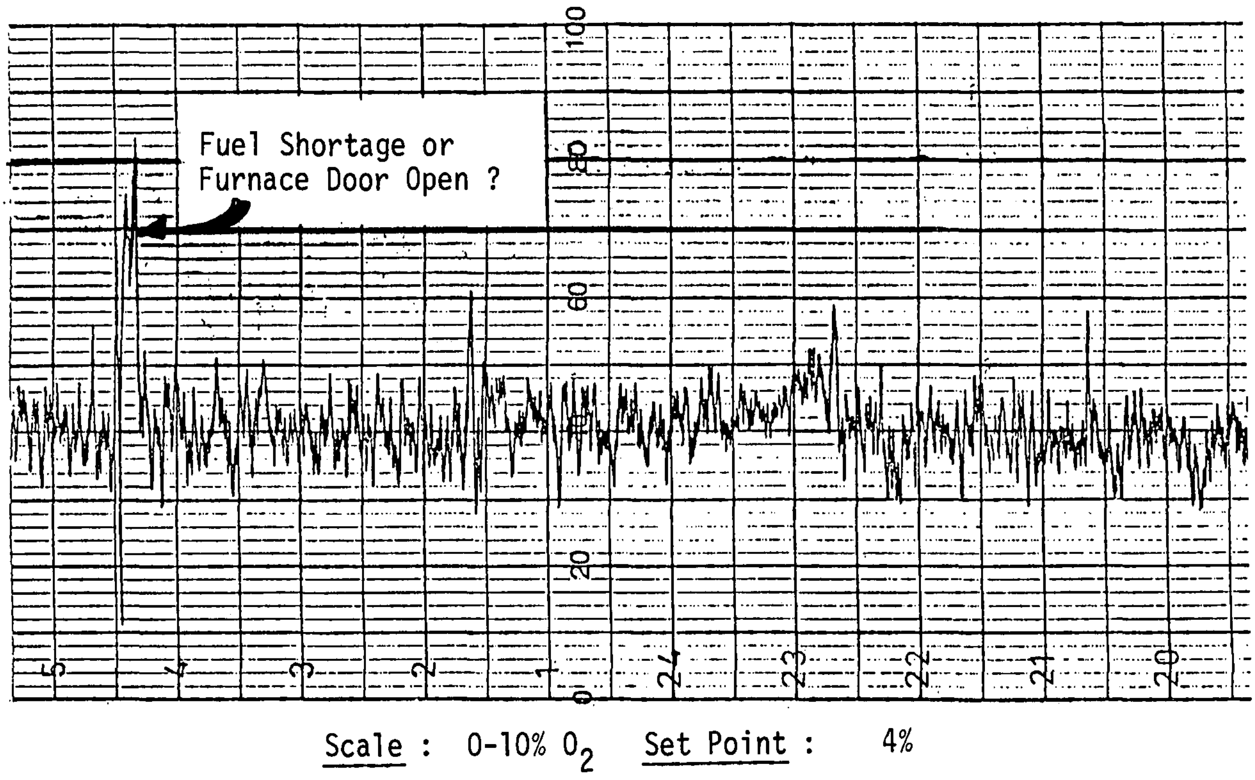


FIGURE 7 Typical O_2 Chart on Bagasse Fuel

Frequent bagasse feeder chokes were initially experienced, until a manufacturing fault was identified and rectified. These chokes severely affected operations for approximately two months but never took the boiler off range completely.

The complete log of stoppages since commisssioning is as follows:

1984

6 June — Boiler commissioned and on range
*10 June — Tripped on low water due to steam flow signal cable burned in bagacillo fire
*12 June — Tripped on low water — instrumentation fault
*14 June — ID fans tripped — electronic fault on DC drive
25 June — First scheduled internal inspection; minor modifications
1 Aug — Factory electrical failure — all boilers tripped
6 Aug — Taken off range to repair grate drive hydraulics
27 Aug — Taken off to clear excessive coal on grate (unnecessary stop)
28 Sept — Second scheduled internal inspection; minor modifications
*10 Oct — Forced draught fan motor burned out

1985

26 Feb — Off range for off-crop

The four asterisked(*) outages were the only unplanned outages, and three of these were within the first eight days. During the last five months of the season only two to three hours were lost when the FD fan motor burned out, after which the boiler was restarted and steamed at 60 to 80 tons per hour for four days on secondary air and ID fans only. Both drum level tripouts (on days 4 and 6) were from causes external to the boiler.

On test at MCR, the boiler operated at an efficiency on NCV of 88,4% on 53% moisture bagasse, the gas exit temperature from the heat recovery equipment being 139°C compared with the design specification of 150°C. O_2 in flue gases averaged 3,7%.

The high efficiency of the boiler was immediately noticeable on the factory fuel balance and in fact minimal coal burning was necessary after its commissioning.

The boiler provided outputs of 180 tph (120% MCR) when required. However, it was only required to provide 120 to 130 tph during most of the season, and this light load would have significantly reduced any erosion. Changes in mill steam usage will result in higher loads during 1985-86, when erosive effects will again be carefully monitored.

Summary

The boiler has performed most satisfactorily during its first season of operation, particularly in regard to the key parameters of high efficiency and reliability.

With its effective O_2 control and final gas temperatures usually reading 130°C or less on bagasse, the NCV efficiency is normally in the high 80's. On coal, the NCV efficiency is approximately 90%, with final gas temperatures of 115 to 120°C.

Reliability has been excellent, with only one unplanned boiler outage in its last 8,5 months operation.

The boiler has remained free of fouling in areas such as cold-end heat recovery equipment and the scrubber despite no maintenance or cleaning stops during the last five months of the season.

There is no evidence of tube erosion from nine months' operation.

It's reliability and ease of operation are particularly appreciated by the boiler operating personnel.

Several unique features of the boiler will be considered for application in future installations, including the modified 3-pass main bank, large steam drum, heat recovery equipment arrangement, integrated scrubber — ID fans — stack and control instrumentation.

Acknowledgements

The assistance of the mill management at Maidstone and of the staff of John Thompson Africa (Pty) Limited in providing information for this paper is acknowledged with appreciation.

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