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COMBUSTION AND EMISSION PERFORMANCE OF A HOG FUEL FLUIDIZED-BED BOILER WITH ADDITION OF TIRE-DERIVED FUEL

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ABSTRACT

Salt-laden hog fuel (wood waste) is burnt in a fluidized-bed power boiler converted from a travelling-grate boiler to generate steam for a specialty paper mill. The converted boiler has a design capacity of 156 t/h of steam from hog fuel, and actual generation varied from 76 to 107% of the design capacity. The conversion resulted in more stable operation, more complete combustion, less ash production, reduced boiler maintenance, and lower fossil fuel consumption. Tire-derived fuel (TDF) is used as a supplementary fuel. With an energy content of 33 GJ/t for TDF, as compared to 8 GJ/t for wet hog, addition of 2–5% TDF by weight increased the bed temperature by an average of 55°C, stabilized and improved the combustion of low-quality hog fuel, and high-moisture-content sludge. We studied the impact of TDF addition in detail. We tested stack emissions, and analyzed bottom and fly ash samples. Although TDF contains 1% zinc and 5 to 7% steel wire, addition of TDF did not affect total particulate emissions from the boiler. SO_2 emissions increased due to the high sulphur content of TDF (1.6%). We obtained a good correlation from the test results, showing that the addition of TDF resulted in a reduction in both the total formation and the stack emissions of dioxins and furans.

RÉSUMÉ

Des déchets de bois imprégnés de sel sont brûlés dans une chaudière énergétique à lit fluidisé convertie d’une chaudière à grille roulante, afin de produire de la vapeur pour une usine de papier à usages spéciaux. La capacité de conception de la chaudière convertie est de 156 t/h de vapeur produite en brûlant des déchets de bois, et la génération réelle variait de 76 à 107 % de la capacité de conception. La conversion a permis d’obtenir un fonctionnement plus stable et une combustion plus complète, et aussi de réduire la quantité de cendres produites, l’entretien de la chaudière et la consommation de combustible fossile. Le combustible dérivé de pneus (TDF) est employé comme combustible d’appoint. En raison de sa teneur énergétique de 33 GJ/t comparativement à 8 GJ/t pour les déchets ligneux humides, l'ajout de 2 à 5 % de TDF par poids a permis d'accroître la température de 55 °C en moyenne, de stabiliser et d'améliorer la combustion des déchets ligneux de qualité inférieure et des boues à forte teneur en eau. Nous avons étudié en détail les effets de l'ajout de TDF. Nous avons analysé les émissions des cheminées et des échantillons de cendres résiduelles et de cendres volantes. Bien que le TDF contienne 1 % de zinc et de 5 à 7 % de fil d'acier, l'ajout de TDF n'a pas modifié les émissions de matières particulaires totales de la chaudière. Les émissions de SO_2 se sont accrues en raison de la forte teneur en soufre du TDF (1,6 %). Nous avons obtenu une bonne corrélation à partir des résultats des essais, ce qui indique que l'ajout de TDF a permis de réduire tant la formation totale que les émissions de dioxines et de furannes dans les cheminées.

KEYWORDS

FLUIDIZED BEDS, WOOD WASTE, HOGGED FUEL, TIRES, COMBUSTION, EMISSION, DIOXINS, FURANS, BOILERS.

INTRODUCTION

NorskeCanada operates a specialty paper mill in Port Alberni, producing approximately 1200 tonnes/day of lightweight coated and groundwood specialty papers. It used to incorporate kraft pulp from an on-site kraft mill. Since the shutdown of the kraft mill in 1993, steam demand for paper manufacture in this mill has been met using three power boilers. The #4 power boiler, a Combustion Engineering boiler, was first installed in 1977. The boiler was originally equipped with a travelling grate and designed to produce up to 38 kg/s (300,000 lb/hr) of 4140 kPa (600 psi) steam from burning hog fuel or a maximum of 57 kg/s (450,000 lb/hr) on Bunker C oil. The older and smaller #2 & #3 power boilers were originally also hog fuel boilers, equipped with fixed grates requiring manual cleaning of grate ash. Several upgrades have been undertaken since then. An electrostatic precipitator (ESP) was installed in 1989. The #4 boiler was converted to a bubbling fluidized bed boiler in 1997. The #2 and #3 boilers now burn natural gas only and produce approximately 10–30% of the steam requirements, while #4 power boiler produces the remaining 70–90% of the steam by burning hog fuel.

Nomenclature

BDt	=	Bone dry tonnes
BFB	=	Bubbling fluidized bed
ESP	=	Electrostatic precipitator
Hog fuel	=	Bark and wood waste
MCR	=	Maximum Continuous Rating for steam generation
ng	=	nanogram (10^{-9} g)
pg	=	picogram (10^{-12} g)
PAHs	=	polycyclic (polynuclear) aromatic hydrocarbons (only the 16 species as required by the NPRI of Canada are included for this study)
PCDDs	=	Polychlorinated dibenzo-p-dioxins
PCDFs	=	Polychlorinated dibenzeno-furans
t/h	=	metric tonnes per hour
TDF	=	Tire derived fuel
TEQ	=	Toxicity Equivalent to 2,3,7,8-tetra-chlorinated dibenzo-p-dioxin
	=	$\Sigma\{(TEF)_i.C_i\}$, where $(TEF)_i$ is the NATO toxicity equivalent factor of dioxin/furan congener i and C_i is its concentration.

EQUIPMENT AND TRIALS

The current hog consumption rate is approximately 700–800 BDtonnes/day or 1800–2000 tonnes/day of wet hog fuel at 60% moisture content. Waste/excess activated sludge is also incinerated in the #4 boiler. Hog fuel presses are used to reduce and even out the moisture content of the hog/sludge fuel blend. Natural gas and/or tire derived fuel (TDF) may also be co-fired in the hog boiler as auxiliary fuel. The flue gases from all three boilers are mixed before discharging to the ESP for particulate removal. The boiler and the hog fuel and TDF delivery system is shown schematically in Figure 1.

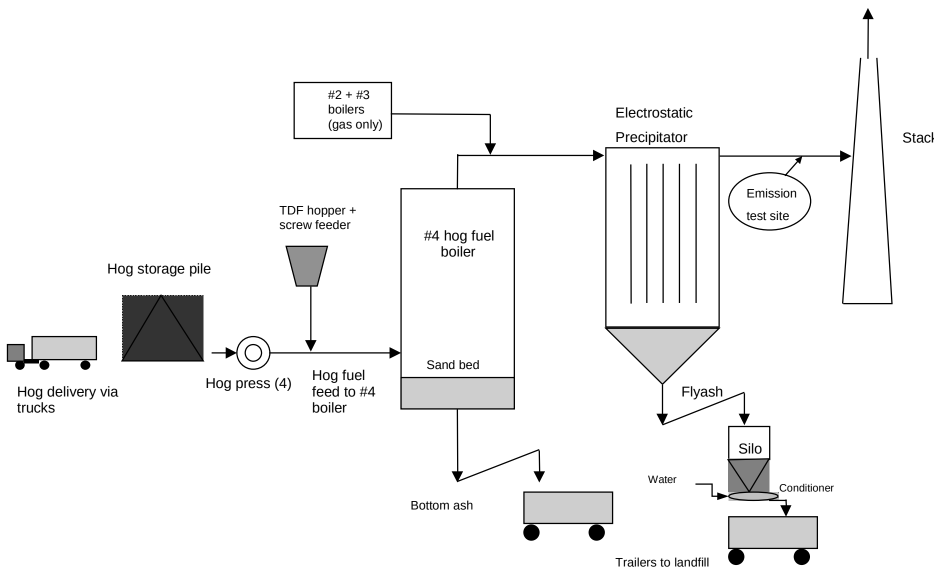

Figure 1. Schematic diagram of the #4 BFB boiler and the TDF and hog fuel delivery system.

Bubbling Fluidized Bed Power Boiler

Mill operating experience indicated that the travelling grate #4 boiler could not consistently achieve the design hog fuel steam generation capacity. Its actual generation rate when burning hog fuel was typically 25 kg/s (200,000 lb/hr). A significant amount of gas/oil had to be burnt to meet the mill's steam demand. The #4 boiler's travelling grate also proved to be mechanically unreliable. Failure of the grate system occurred each year resulting in high repair costs and additional fossil fuel costs during the repairs. In addition, the mill was receiving increasing quantities of low quality hog fuel produced from dryland log sort operations. A reliable system for combustion of this hog fuel was required to avoid environmental disposal problems (land filling). The existing grate systems were not suited to the higher sand and rock content of the dryland sort hog fuel.

To accommodate the lower quality hog fuel, the #4 boiler was converted to a bubbling fluidized bed boiler in 1997. The converted bubbling fluidized bed boiler (BFB) allowed all of the hog fuel and wood waste available from the forest industry operations in the Port Alberni area (sawmills, logging divisions & paper mill), as well as the waste sludge from the mill's effluent treatment plant, to be burnt in a single boiler. The #2 & #3 power boilers would operate on fossil fuel only to meet the total mill steam requirements, avoiding needed repairs to the fixed grate hog burning systems on these boilers. Major components of the conversion included:

- Removal of the lower 25 feet of the boiler
- Replacement of the lower boiler
- Reconfiguration of the hog feed system
- Upgrading of the start up burner system
- Addition of a three-level combustion air system and a coarse ash removal system to handle lower quality "dryland sort" fuels containing sand and rocks
- Installation of a dry flyash conveying and storage system

The converted BFB boiler has the following features:

- Generation of 43 kg/s (343,000 lb/hr) of steam at 400°C and 600 psi from hog fuel, as compared to 25 kg/s of steam that could be generated by the travelling grate boiler.
- Combustion of 228,000 BDt/year of hog fuel @ 60% moisture content and 45 BDt/day of sludge @ 70% moisture content
- A total of 6 hog feeders, 3 on each of the side walls
- No supplemental fossil fuel
- Local sand is used as the bed material. The boiler bed holds approximately 70 tonnes of sand.
- No solids recirculation/return to the bed/boiler
- Ash is collected from the boiler bottom, air heater/economizer, multi-cyclones, and the ESP.
- Combustion air is heated by flue gas through a tube air heater, located upstream of the economizer.
- Combustion air is introduced as primary (ca. 50% of the total air), secondary, and tertiary (including load burners) air. Primary air is the fluidizing air.
- Fluidizing air is distributed through capped nozzles with holes on the sidewalls. The superficial fluidizing gas velocity is about 2 m/s at operating temperatures.

Startup of the converted BFB boiler went smoothly and design parameters were readily met, with the boiler operating at the Maximum Continuous Rating (MCR) two weeks following startup. More complete combustion and a reduction in the unburnt carbon content of the ash were observed with the fluidized bed upgrade. No changes to the existing precipitator/emission control system were required.

Tire Derived Fuel

The shutdown of a local sawmill late in 1997 eliminated the highest quality hog fuel source (low moisture, high heating value, low sand & rock content). At the same time, substantially higher volumes of hog fuel produced from dryland log sort debris were received, which had high sand and ash content (10–25%). This significant change in fuel characteristics immediately and negatively impacted the hog fuel burning rate. It was decided to pursue addition of an alternative solid fuel to improve the combustion performance.

Tire Derived Fuel (TDF) was chosen as the auxiliary fuel. Produced by shredding waste automobile and truck tires, TDF is a cheap fuel. It has a high heating value with low moisture content. There are plenty of scrap tires available and co-firing TDF in a power boiler is an attractive tire disposal option. For example, TDF has been utilized in power generation plants and pulp and paper mills in the US as a supplemental fuel. Twenty US mills consume approximately 35 million tires annually [1]. The primary benefit is to assist with the combustion of high moisture sludge. Addition rates were typically 10%. Tires were already being used as a fuel at two cement kilns in British Columbia.

The TDF burnt in this boiler is produced by Target Recycling Inc., which has a tire recycling plant in Port Alberni. In preparing the TDF, tires are shredded to produce “chips” approximately 5 cm in size or smaller. The heavy bead or rim wire is removed prior to shredding. Additional radial wire is removed magnetically. The composition of the TDF burnt in this boiler, shown in Table I, is similar to that found in the literature [2]. The energy value of TDF is very high compared to that for typical hog fuel, 8 GJ/t (3400 BTU/lb) of wet hog or 20 GJ/t (8500 BTU/lb) on a dry basis.

TABLE I.
*Tire Derived Fuel Analysis**

	Unit	*Content*
Energy Value	*GJ/tonne*	*33*
	BTU/lb	*14,300*
Sulphur	*%*	*1.6*
Zinc	*%*	*1*
Wire	*%*	*5–7*
Moisture	*%*	*~ 10*

** Based on 5 samples collected in 1998–99*

TDF Trials

A trial permit was granted by the BC Ministry of Environment to allow addition of a maximum of 40 tonnes/day TDF to the hog fuel (5% by weight) for a period of one year. A technical literature review conducted on burning low amounts (<10%) of TDF in pulp and paper mill hog fuel boilers indicated the following potential environmental issues:

Particulate emissions: An efficient particulate control device (e.g. ESP) is required to prevent increased particulate emissions when burning TDF. A proper feed system to provide a consistent and well-controlled TDF feed rate is recommended.

Proper combustion air control on the boiler is required to ensure efficient combustion of the TDF.

Zinc emissions: Rubber tires contain approximately 1% zinc as part of the tire formulation. The zinc is oxidized to very fine zinc oxide particles in the boiler, which can subsequently be captured by an ESP. As a result, the zinc content of the flyash will increase. The zinc will tend to remain insoluble due to the high pH of flyash. The literature indicates that little or no increase in zinc would be expected in the boiler bottom ash [2].

Sulphur: The sulphur content of TDF will be converted to sulphur dioxide in the boiler. The significance would depend on the amount of TDF added, the sulphur content of other fuels and specific mill emission permit limits.

Other emissions: There was limited information available on other trace toxic organic emissions from low TDF addition rates to pulp and paper boilers at that time (most studies related to dedicated tire incinerators or lab scale studies). One study indicated little or no change in polynuclear aromatic hydrocarbons (PAH) emissions from two wood-fired power boilers burning 2–7% TDF [3].

Local environmental issues: The mill agreed that TDF addition must not negatively impact emissions or air quality.

Based on the above concerns, the permit specified the following testing requirements:

- stack emissions — total particulate, metals, SO_2
- flyash and bottom ash — metals
- bottom or coarse ash — leachate

The TDF trials were conducted from March 1998 to March 1999. In the first phase of the trials, TDF was manually added to the main hog fuel conveyor at a rate equivalent to 2% of hog fuel (one 12-liter bucket every 30 s). Based on the positive results from the initial trials, a feed hopper with variable speed screw feeder was installed for the second phase of the trials and following operations. The hopper (see Figure 1) holds approximately 8 tonnes of TDF. Bridging can be minimized using a spike roll located above the screw and operated by a pneumatic cylinder. The screw feeder was calibrated by collecting and weighing TDF discharged from the screw. During operation, the screw feeder discharges onto the hog fuel conveyor leading to the boiler (Figure 1). The TDF feed system is interlocked to the hog fuel conveyor system. The TDF feeding rate was increased to 5% of the hog fuel in the second phase. A total of 1300 tonnes of TDF was consumed during the trial period, equivalent to approximately 150,000 passenger tires.

The trials were successful and the emission testing and ash analysis results were satisfactory [4]. The BC Ministry amended the air permit for the boiler in September 1999 to authorize the use of up to 5% TDF on an ongoing basis. TDF has now been routinely added to #4 BFB power boiler for over four years. Many stack emission tests and ash analyses have been carried out since then and significant efforts have been made to correlate combustion and emissions performance to operating conditions. Some of the results obtained during the trials and routine operations, including stack testing results, are summarized in the following discussion.

RESULTS AND DISCUSSION

Boiler Operations

The mill's DCS system records major operating conditions, including the steam load, air supply, TDF addition rate, bed temperature, and downstream temperatures (at the generating bank, air heater, economizer and ESP). The sand in the fluidized bed will start to clinker or fuse at temperatures of 1090°C. The operating limit is set at 870°C to provide a significant safety margin. One or more of the bark presses would have to be bypassed to keep the hog moisture content high in case the bed temperature increased beyond the acceptable range.

Stack and ash tests have been carried out regularly for both compliance and research purposes. In particular, stack dioxin emissions have been closely monitored, as this boiler burns salt-laden hog fuels. Dioxin control techniques have also been tested. In an effort to correlate the combustion and emission performance, testing and sampling activities are carefully coordinated with operation and measurement plans. For each test, while the stack fluegas is being sampled, hog and ash samples are also taken. Stack testing is normally for particulate, CO, CO_2, O_2, SO_2, HCl, dioxins/furans, and PAH emissions, while ash samples are analyzed for metals, unburnt carbon, dioxin/furans, and PAHs. Hog samples are used to determine the hog salt and moisture contents. Meanwhile, bed and free board combustion conditions are observed through the furnace windows and the temperature profile in the furnace is measured with a laser pyrometer.

Table II compares the operating conditions and emission results for two of the recent tests, one conducted in winter and the other in summer. The winter hog fuel was wet containing 60% moisture, as compared to 55% moisture in the summer hog. Steam demand is usually higher in winter than in summer. TDF was co-fired at the rate of 5% during the winter test to assist combustion of the wet hog for a high steam load (98% of the full capacity). However, no TDF was added in the summer test. Actually, the sand bed would have been overheated if TDF had been co-fired with the dryer summer hog.

The comparison indicates that the winter operating parameters, with a wetter hog and with the co-firing of 5% TDF, become very similar to the summer parameters except for a higher unburnt carbon content in ash and higher SO_2 emissions. Higher SO_2 emissions are expected with the addition of TDF as the TDF contains 1.6% sulphur. The higher unburnt carbon (lower thermal efficiency) may have resulted from the higher steam load (98% MCR). An increase in ash carbon content is clearly shown in Figure 2 with increasing steam load. The generally low ash carbon content (maximum of 15%) confirms the excellent combustion performance of this BFB boiler with or without co-firing TDF.

TABLE II.
Examples of Summer and Winter Operating Conditions and Emission Results

Parameter	*Unit*	*Feb-7-02*	*Jun-6-02*
Steam generation rate	*tonne/h*	*153*	*141*
As % of MCR	*%*	*98.5*	*90.7*
Fluidizing air flow	*tonne/h*	*117*	*115*
As % of total air	*%*	*48*	*49*
Fluidizing air T	*°C*	*255*	*259*
Superficial fluidizing velocity	*m/s*	*2*	*2*
2nd + start burners air	*tonne/h*	*39*	*49*
As % of total air	*%*	*16*	*20*
3rd + load burners air	*tonne/h*	*90*	*72*
As % of total air	*%*	*36*	*31*
Bed height	*cm*	*53*	*53*
Bed temperature	*°C*	*844*	*887*
Lower furnace T (1st floor)	*°C*	*1032*	*1033*
Upper furnace T (5th floor)	*°C*	*911*	*927*
Air heater inlet fluegas T	*°C*	*397*	*407*
Economozer inlet fluegas T	*°C*	*297*	*287*
ESP temperature	*°C*	*165*	*164*
Hog moisture content	*%*	*60.6*	*55.4*
Hog salt content	*% Cl*	*0.12*	*0.23*
TDF addition rate	*%*	*5.0*	*0*
Boiler exit oxygen	*%*	*4.1*	*2.4*
Flue gas CO	*ppm*	*359*	*347*
Particulate emissions	mg/m^3	*<10*	*<10*
SO_2 *emissions*	mg/m^3	*127*	*65*
PCDD/Fs, TEQ@11% O_2	ng/m^3	*0.014*	*0.289*
PAHs @ 11% O_2	$\mu g/m^3$	*0.51*	*14.8*
Dioxins/furans in ash	*pg/g*	*1690*	*1150*
Unburnt carbon in ash	*%*	*11.5*	*4.2*
Opacity, before ESP	*%*	*74.7*	*78.5*

More test data are available for further examination of the combustion performance. Fifteen of the results, obtained with 2.5–5% TDF addition, indicated an average steam generation rate of 342 klb/h (100% MCR) from hog/sludge/TDF blends @ 60% moisture content. The average steam rate of the other eleven tests was 313 klb/h (91% MCR) from hog/sludge blends @ 57% moisture content.

The above comparison and extended operating experience suggests that TDF is an excellent supplemental fuel for this BFB boiler. Operational experience and benefits of TDF co-firing are summarized as follows:

- Stabilization of boiler operation when burning lower quality hog fuel; this is especially apparent during weekend operations when the best quality hog fuel from the local sawmills is not delivered.

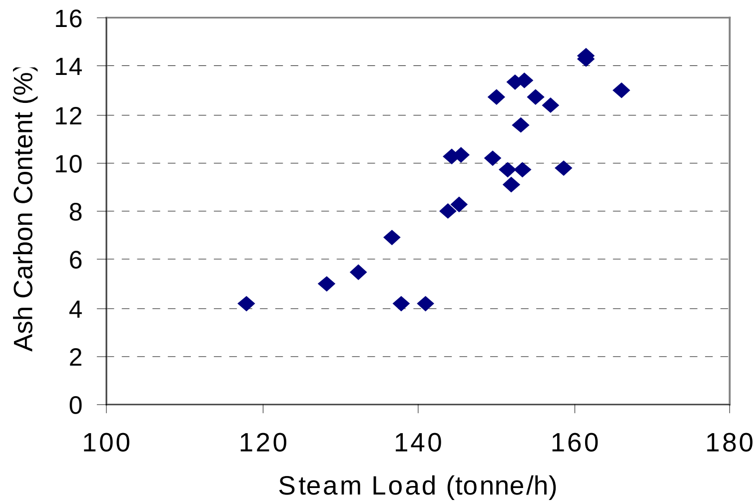

Figure 2. Effect of steam load on unburnt carbon content of flyash.

- Increased fluidized bed temperatures, approximately 55°C on average.
- An approximately 5% increase in hog fuel burning rates, no negative impacts on boiler operation and no problems with removal of the bottom ash were experienced.

Major Emissions

Air emissions measured during the one-year TDF trials, and reported previously [4], indicated that the average particulate emissions were 73 mg/m^3, as compared to the permit limit of 230 mg/m^3, and the average SO_2 emissions were 26 ppmv. In these initial trials the addition of TDF did not appear to affect the PM or SO_2 emissions.

In the present work, stack tests conducted after the completion of the TDF trials showed better PM emission results, as illustrated in Table III. Again, however, PM emissions were not significantly affected by co-firing TDF.

Average CO emissions in 24 tests were 248 ppmv. CO emissions apparently increased with increasing TDF addition rate. However, an increase from 200 ppm to 330 ppm is not considered to be dramatic and, to a large extent, can be attributed to the higher steam loads and poorer hog quality associated with winter operations when TDF is co-fired.

There was no impact of TDF addition on HCl emissions, while SO_2 emissions were higher with the addition of TDF due to the addition of sulfur contained in the TDF. However, the absolute level of emissions remained relatively low compared with those from coal and oil fired power boilers. The SO_2 emissions from this boiler, if and when regulated in the future, can be readily controlled, for example, by introducing limestone into the fluidized bed.

TABLE III.
Effect of TDF addition on stack emissions

	Unit	TDF Addition Rate 0%	2.5%	5%
No. of tests		*8*	*5*	*6*
*PM**	*mg/m^3*	*7.4*	*18.1*	*3.0*
No. of tests		*4*	*1*	*2*
SO_2	*ppmv*	*18.6*	*52.2*	*49.4*
No. of tests		*4*	*1*	*2*
HCl	*ppmv*	*42*	*45*	*42*
No. of tests		*13*	*5*	*6*
CO	*ppmv*	*200*	*278*	*328*

** Based on filter gains only; for research and information purposes.*

Metals in the stack emissions were analyzed and the results were reported previously [4]. The bulk of the stack particulate is sand (silica) and wood ash, while Zn and Fe were 0.26% and 5.5%, respectively. Although TDF contains a high content of zinc and iron, the addition of TDF did not increase stack emissions of any of the metals compared with the baseline measurements. Other metals such as arsenic, cadmium and lead were at or below the detection level.

Ash Residuals

The #4 BFB power boiler produces two ash residuals, flyash and bottom ash.

Flyash — Lightweight wood ash, salt and fine sand, which is emitted from the top of the boiler. These materials are captured in the air-heater/economizer hoppers, multicyclones and ESP. Flyash is collected dry in a silo and a small amount of water is added just prior to discharging to a transport trailer to reduce dusting. Approximately 30–40 tonnes/day of flyash is landfilled.

Bottom ash — Coarse material such as gravel and rocks from the incoming hog fuel and sand from the fluidized bed, which is removed by screw conveyors under the boiler. Approximately 10–20 tonnes are removed and replaced daily. The bottom ash is stockpiled and re-screened. The fine sand portion (< 1 mm) is reused for sand bed makeup. The over-sized material (rocks & gravel) goes to landfill.

Metals analyses for the flyash and unscreened bottom ash are shown in Table IV. Both ash residuals were also tested according to the BC Special Waste Leachate Extraction Procedure (Special Waste Regulations). The leachate extraction test is used to determine the potential of the ash to release metals in an acidic environment. This is a "worst case" condition as the flyash is actually alkaline.

As expected, the iron and zinc contents of both the flyash and bottom ash increased with TDF burning. Zinc in the leachate extraction test increased but remained well below the Special Waste Regulation limits. Sodium and chloride were analyzed in the flyash generated with and without TDF co-firing. Their content on the ash depended primarily on the hog salt content and was not affected by TDF addition. Based on five tests with average hog chloride content of 0.12%, the flyash samples contained an average of 0.89% Na and 1.93% Cl. Other metals not listed in the table, such as As and Hg, were all below the detection limits for both the "no TDF" and "TDF" samples.

TABLE IV.
Ash metals analysis

	Unit	*BC limit*	***TDF Addition Rate*** 0%	2%	5%	0%	**2%**	5%
				Flyash			***Bottom ash***	
No. of tests			*3*	*4*	*4*	*3*	*3*	*1*
Cadmium	*ppmw*		*1*	*0.7*	*0.9*			
Chromium	*ppmw*		*53*	*53*	*48*	*28*	*29*	*18*
Nickel	*ppmw*		*27*	*29*	*25*	*20*	*21*	*15*
Iron	*%*		*2.43*	*3.73*	*4.03*	*1.74*	*2.76*	*2.53*
Lead	*ppmw*		*55*	*40*	*57*			
Zinc	*%*		*0.04*	*0.26*	*0.64*	*0.02*	*0.13*	*0.29*
Leachate test	*mg/L Zn*	*500*	*4.6*	*20.8*	*104*	*0.38*	*8.1*	*12.9*

PCDD/Fs and PAHs

Polychlorinated dioxins (PCDDs) and furans (PCDFs) and polynuclear (or polycyclic) aromatic hydrocarbons are toxic semi-volatile organic compounds. PAHs are formed in most combustion and thermal processes, while PCDD/Fs may also be formed in the presence of chlorine or chloride.

The hog fuel burned in the power boiler at Port Alberni contains sodium chloride absorbed from the seawater during transportation and storage of logs. Combustion of salty hog fuel is known to produce trace levels of dioxins and furans [5,6]. This was confirmed by stack tests and ash sample analyses for this BFB boiler. However, as reported previously [4], the results from the TDF trials indicated that there was no negative impact on PAH and PCDD/F emissions and no negative impact on the levels of dioxin and furan formation when TDF was added to this boiler. Many more stack and ash tests have been carried out over the past three years following the one-year TDF trials. The level of PAH formation and emissions seems to be slightly lower with TDF addition, as shown in Table V, but a clear effect cannot be established. Stack PCDD/F emissions are significantly lower with the addition of TDF, averaging 0.119 ng TEQ/m^3 @11% O_2 with the addition of 5% TDF, as compared to 0.295 ng TEQ/m^3 @11% O_2 measured without TDF. The average ash PCDD/F concentration is reduced from 3.80 to 2.63 ng TEQ/g by co-firing 5% TDF. A summary of individual test results for dioxins and furans is shown in Figures 3 to 5.

TABLE V.
*Effect of TDF addition on formation and emissions of PAHs and PCDD/Fs**

	Unit	*TDF Addition Rate*		
		0%	*2.5%*	*5%*
No. of tests		*7*	*3*	*6*
Stack PAHs	*µg/m³ @ 11% O_2*	*2.4*	*0.5*	*2.0*
No. of tests		*3*	*3*	*2*
Ash PAHs	*µg/g*	*114.1*	*45.8*	*93.3*
No. of tests		*8*	*3*	*6*
Stack PCDD/Fs	*ng TEQ/m³ @ 11% O_2*	*0.295*	*0.175*	*0.119*
No of tests		*13*	*5*	*6*
Ash PCDD/Fs	*ng TEQ/g*	*3.80*	*2.99*	*2.63*

** The hog fuel tested contained 0.072 – 0.585% chlorine.*

Figures 3 and 4 indicate that both stack TEQ emissions and ash TEQ concentrations increase “linearly” with the fuel Cl/S ratio (correlation coefficients R^2 = 0.87 and 0.71). If the same stack dioxin emissions and ash dioxin concentrations are plotted, respectively, against hog chloride content (not shown here), the correlation coefficients would be significantly lower (R^2 = 0.73 and 0.44). These results confirm the positive attenuating effect that sulphur has on PCDD/F formation, in agreement with the literature [7–9]. Since the contribution of sulphur from hog fuel and sludge is relatively small and largely constant, it may be concluded that addition of TDF can reduce PCDD/F formation and emissions because of its high sulphur content (1.6%).

It has been reported that copper is the most active catalyst for *de novo* formation of dioxins, followed by iron [9–11]. In an attempt to relate dioxin and furan formation to the level of catalysts present, flyash samples from this boiler were also analyzed for Cu and Fe. The ash Cu content was found to be in the range of 75–185 ppmw with no correlation to the ash TEQ concentration. The Fe content of the flyash was a few orders of magnitude higher, as shown in Figure 5, in the range of 1.5–5.1%. It would, therefore, be reasonable to assume that iron should be the dominant catalyst for de novo formation of PCDD/Fs in this boiler. However, the ash TEQ concentration was found to decrease with increasing ash Fe content up to 2%, with little dependency at higher Fe contents. This behavior may be explained considering the properties of TDF. While the iron component of TDF might catalyze the formation of dioxins and furans, the sulfur component would inhibit the formation. For the data in Figure 5, the ash samples with Fe contents of >2% were generated in the presence of TDF and the rest of the samples were from combustion of hog/sludge fuel alone. The lower ash TEQ concentrations at higher iron contents again confirm that co-firing TDF can reduce PCDD/F formation.

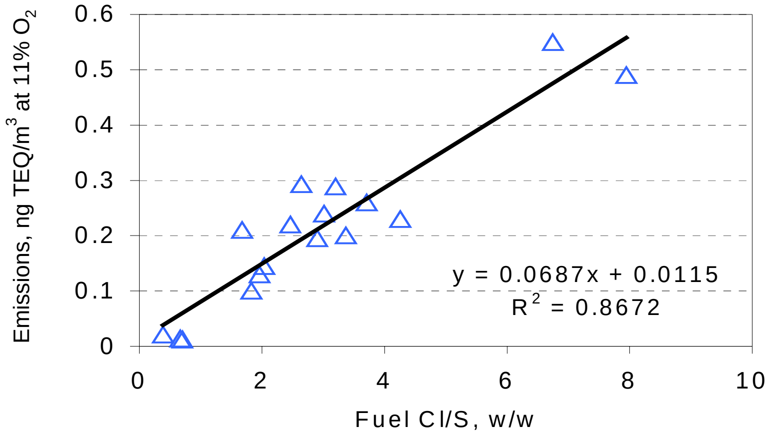

Figure 3. Effect of fuel Cl/S ratio on stack TEQ emissions

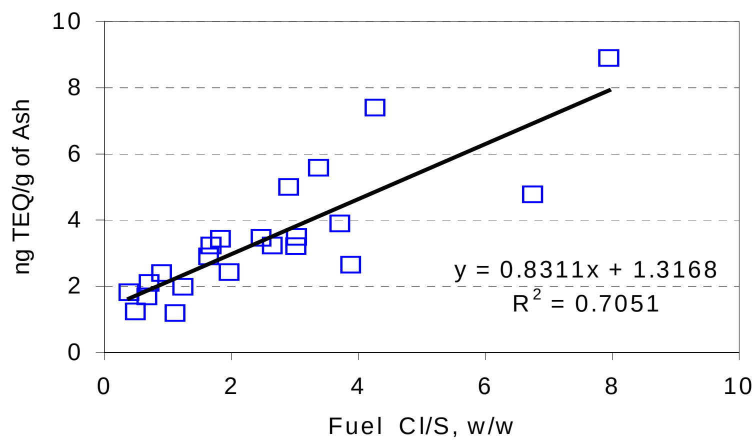

Figure 4. Effect of fuel Cl/S ratio on ash dioxin and furan concentrations.

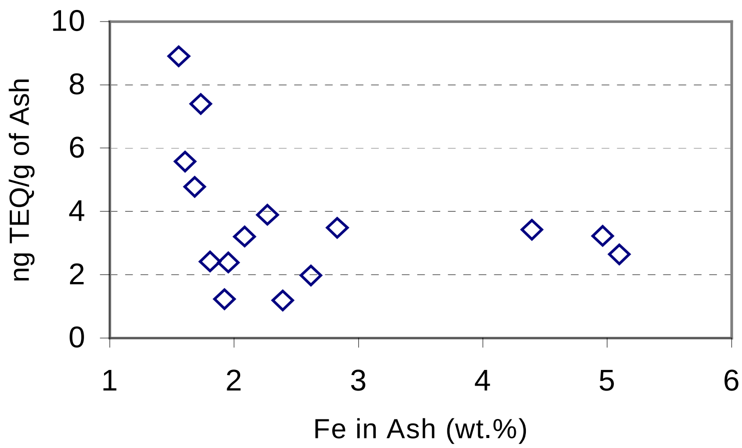

Figure 5. Correlation of ash TEQ to ash iron content.

SUMMARY

The conversion of the travelling grate hog fuel boiler to a bubbling fluidized bed boiler was a success as it increased combustion efficiency and steam production from hog fuel. Addition of up to 5% tire derived fuel stabilized the operation of the fluidized bed boiler when low quality hog fuel was burnt. The hog fuel combustion rate increases and fossil fuel requirements decrease when TDF is co-fired in the BFB boiler.

The TDF addition rate is limited by the maximum tolerable fluidized bed temperature and must be reduced or discontinued with good quality hog fuel. Stack emissions of total particulate, CO, HCl, and metals are not affected by TDF addition. SO_2 emissions increased from 20 to 50 ppmv with TDF addition. The zinc content of the flyash captured in the ESP increased from 410 to 6300 ppmw with TDF addition but continues to meet the regulated limits. TDF addition did not affect stack PAH emissions and ash PAH formation. Both stack dioxin and furan emissions and ash dioxin and furan concentrations were reduced with TDF addition. Co-firing TDF with hog fuel in a BFB boiler is an environmentally sound and economically viable solution to waste tire disposal.

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