VALIDATION OF FIRESIDE PERFORMANCE INDICES: FOULING/CORROSION EVALUATION OF MDF PARTICLEBOARD AND BLENDS WITH WHEAT STRAW BOARD

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EXECUTIVE SUMMARY

Sauder Woodworking, which currently fires a large portion of all wood wastes in a boiler producing process steam, is investigating using particleboard made from wheat straw in its manufacturing process and is concerned with the effects of higher levels of ash and potassium on its boiler. A project was undertaken to investigate the potential detrimental effects of firing blends containing wheat straw on boiler tube fouling and corrosion. Additional funding for this project was provided through the U.S. Department of Energy Jointly Sponsored Research Program (DOE JSRP) project "Validation of Fireside Performance Indices" to validate, improve, and expand the PCQUEST (Predictive Coal Quality Effects Screening Tool) program. Since there are differences in the chemical and mineral form of the inorganic content in biomass and substantial differences in organic matrix characteristics, analysis and characterization methods developed for coal fuels may not be applicable. The project was seen to provide an excellent opportunity to test and improve the ability of PCQUEST to handle nontypical soil and biomass minerals.

Samples of wood fiberboard and wheat straw board were analyzed for proximate, ultimate, heating value, and bulk ash composition. Advanced analyses using computer-controlled scanning electron microscopy (CCSEM) and chemical fractionation were also performed, along with combustion tests using the baseline medium-density fiberboard (MDF) particleboard and blends of 95–5, 90–10, and 80–20 MDF–wheat straw to determine fouling propensity and deposit strength development. Corrosion testing of the fly ash produced for the baseline and blends was performed on three candidate steels with test durations of 500 and 1000 hours at temperatures of 750° and 1100°F.

All blends containing wheat straw exhibit increased fouling relative to the baseline MDF. The best candidate blend ratio for wheat straw waste firing in the existing Sauder boiler is the 95–5 MDF–wheat straw blend. Fouling and deposit strength are both expected to be greater than the baseline MDF waste but may be manageable with an increase in sootblowing. Blends containing higher percentages (>5%) of wheat straw board waste are not recommended because of the formation of problematic deposits of high strength that may lead to blocking of convective passages.

Results from corrosion tests indicated a general trend toward increasing wastage of each metal for blends containing wheat straw board. As expected, corrosion was also shown to be temperature-dependent, as the samples maintained at 750°F showed lower levels of corrosion than their 1100°F counterparts. Of the three metal samples used, the carbon steel suffered the greatest corrosion, with significant wastage observed over all test conditions. The Hastelloy and stainless steel indicated the best resistance to corrosion, with minimal wastage at the low temperature and slightly greater wastage at the higher temperature. The stainless steel also had

significantly greater corrosion resistance than the carbon steel, with slightly less resistance than the Hastelloy.

Advanced analyses on each fuel will be used as input for PCQUEST modeling to examine the effects of blends containing wheat straw on high-temperature fouling, low-temperature fouling, opacity, furnace wall slagging, and sootblower effectiveness (deposit strength). Because the model was developed to distinguish expected behavior between various coal types, the indices may require modification for applications with biomass, particularly with the wheat straw board. Test results will be used to establish the differences existing (if any) between biomass ash fouling and coal ash fouling. This project is continuing under the new Cooperative Agreement with the U.S. Department of Energy, and the PCQUEST modeling results will be included in the final report to be submitted when the project is completed.

VALIDATION OF FIRESIDE PERFORMANCE INDICES: FOULING/CORROSION EVALUATION OF MDF PARTICLEBOARD AND BLENDS WITH WHEAT STRAW BOARD

1.0 INTRODUCTION

Sauder Woodworking currently fires a large portion of all wood wastes in a boiler producing process steam. It is investigating using particleboard made from wheat straw in its manufacturing process and is concerned with the effects of the inorganics on its boiler. Wheat straw board contains higher ash contents and increased levels of potassium, creating concern over fouling characteristics in Sauder's tight boiler design. In addition, the wheat straw board contains high concentrations of chlorine, which may affect boiler tube corrosion when fired in combination with the particleboard wastes currently generated. Sauder has engaged the services of the Energy & Environmental Research Center (EERC) at the University of North Dakota to investigate the potential detrimental effects of firing blends containing wheat straw on boiler tube fouling and corrosion.

Additional funding for this project was provided through the U.S. Department of Energy Jointly Sponsored Research Program (DOE JSRP) project "Validation of Fireside Performance Indices" to validate, improve, and expand the PCQUEST (Predictive Coal Quality Effects Screening Tool) program. The PCQUEST fuel database is constantly expanding and adding new fuels, for which the algorithms may need refinement and additional verification in order to accurately predict index values. A key focus is on performing advanced and conventional fuel analyses and adding these analyses to the PCQUEST database. Such fuels include coals of all ranks and origins, upgraded coals, petroleum coke, biomass and biomass–coal blends, and waste materials blended with coal. Since there are differences in the chemical and mineral form of the inorganic content in biomass and substantial differences in organic matrix characteristics, analysis and characterization methods developed for coal fuels may not be applicable. The project was seen to provide an excellent opportunity to test and improve the ability of PCQUEST to handle nontypical soil and biomass minerals.

2.0 GOALS AND OBJECTIVES

The performance goals to be addressed include validation and improvement of the fouling and slagging indices for a biomass or renewable fuel. The fuels being tested are wood- and wheat straw-based fuels generated as waste sawdust at furniture mills owned and operated by Sauder Woodworking. Current PCQUEST indices have been formulated primarily for coal-based fuels so it is anticipated that the indices may need to be modified for this type of biomass. The current fouling and slagging algorithms are of the following form:

Fouling Index {([pyrite + clays] × organically bound calcium) + organically bound magnesium + (calcite + dolomite)} + {2 × (organically bound Ca + Mg + Na + K) × (included quartz + clays)^2} + {(organically bound Na)^5 ×

(included quartz + clays)} + {(organically bound Ca + Mg + Na + K + Al + Fe + Ti + P)/ash}

Slagging Index {([pyrite + clays] × organically bound calcium) + organically bound magnesium + (calcite + dolomite)} + {($MgO + Na_2O + K_2O$) × (included quartz + clays)} + (included pyrite + clays) + {quartz/(illite + montmorillonite + kaolinite)}

Specific impacts of potassium from the woodboard and strawboard chemical structure and chlorine from the gluing compounds in the woodboard sawdust will be assessed, along with the impacts of boiler type and furnace exit gas temperature. Input criteria for potassium, chlorine, and boiler configuration may need to adjusted.

The project will provide critical analytical and experimental combustion data for determining the fouling, slagging, and corrosion effects of potassium, chlorine and, possibly, other inorganic compounds that may comprise the wood- and wheat strawboard fuels. Because of limited project funding and the primary concern of the commercial sponsor, only the fouling and slagging indices will be considered for improvements with this project. However, the feasibility of potentially adding a corrosion index to PCQUEST will be evaluated. The data to be generated and used to modify the ash fouling and slagging indices include the following:

- CCSEM and conventional coal analysis of the wood fuel and strawboard fuel to be used as input for PCQUEST.

- Experimental combustion testing using the 40,000-Btu/hr CEPS to assess fouling and slagging and essentially calibrate the biomass fuels against coal-based fuels with known deposition severities. Measurements in the CEPS that will be used to assess deposit severity are visual observation of deposit growth and ash sticking, ash deposit growth measurement, ash deposit crushing strength, ash deposit chemistries and associated calculated liquid-phase viscosities, and ash deposit porosity.

This report summarizes work performed during the last year (1998) under the "Validation of Fireside Performance Indices" Cooperative Agreement Jointly Sponsored Research Program just ending. The project is continuing under the new Cooperative Agreement. Figure 1 shows the tasks and milestones for both phases of the project. The major work remaining to be performed under the new agreement includes completion of the fuel CCSEM analyses and corrosion testing and the preparation of the final report.

3.0 BACKGROUND

Energy production from biomass fuel sources such as wood wastes, municipal wastes, agricultural wastes, and landfill or digester gases is currently only about 1% of the total U.S. output (1). However, recent projections show that production capacity could rise to 10% of the

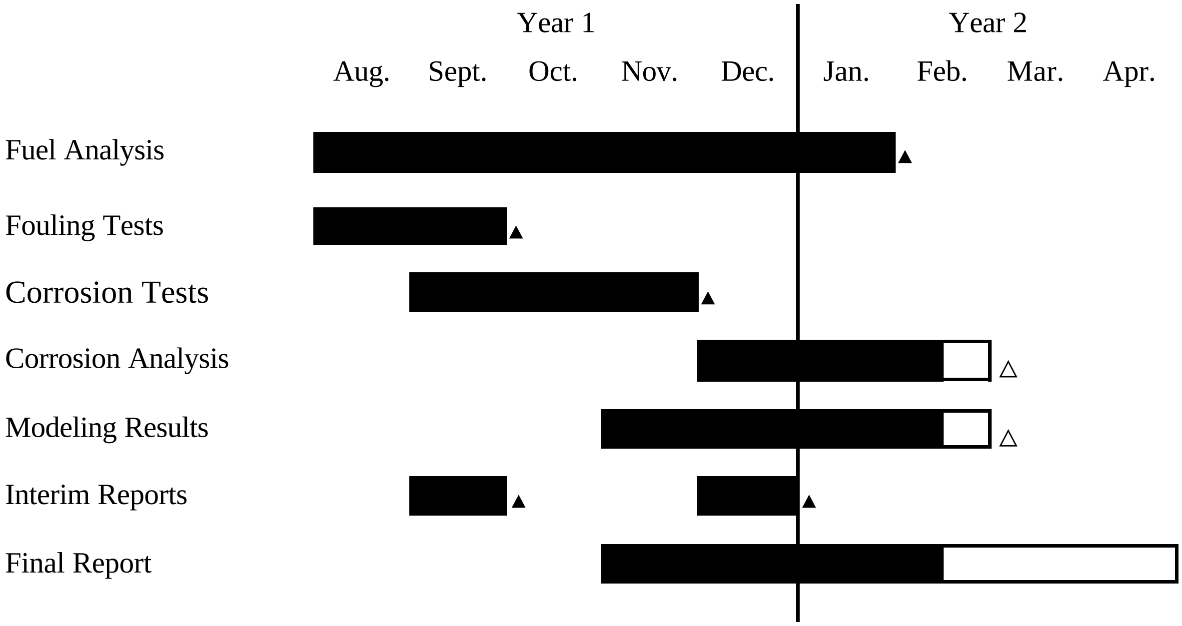

Figure 1. Tasks and milestones.

total U.S. output by the year 2010 (2), if more utilities take on cofiring strategies and if dedicated sources of energy crops are produced (3). Some experts are estimating that 14%–15% of total world energy consumption is accounted for by biomass (4). Two types of biomass are available in the United States, for use as a cofiring fuel with coal in pc-fired boilers: biomass wastes and biomass energy crops (5, 6). Waste products include wood wastes (wooden pallets, telephone poles, sawdust), agricultural wastes (peach pits, rice hulls, straws of wheat, alfalfa, rape, timothy, barley) and municipal solid wastes or sludges. Energy crops include fast growing switchgrass and hybrid trees such poplar and willow. European research into direct and cofiring biomass with coal for power generation has been fairly extensive with various agricultural waste product fuels (7–13); research in the United States has been fairly extensive with wood wastes (14–21), and other fuels have been studied (22–25). A recent synopsis of biomass for energy production, written by European researchers, discussed issues and barriers to using biomass such as wood for energy production (26). In Europe, biomass has been implemented for energy production much more so than in the United States. Biomass combustion is summarized as having the following impacts: being excellent at reducing greenhouse gases, decreases NO_x, destroys polychlorinated biphenyls (PCBs), decreases smog, increases volatile organic compounds (greatly dependent upon combustion process), decreases CO, stimulates landscape and forest conservation, and reduces soil erosion if the wood source is from dedicated resources such as tree farms (26, 27). Blending of this supplemental fuel would hopefully lower coal fuel costs (27) and provide a service to the community surrounding the power plant by creating business opportunities and economic development and by posing a solution to a potential biowaste disposal problem from tree harvesting.

With respect to biomass feeding into conventional coal-fired systems, various utilities in Europe and the United States have either developed size-reducing methods that work for injecting the usually more fibrous and pliable biomass fuel into the boiler or, in many cases, installed separate injection ports (7, 8, 18, 24). Wood has characteristically been more of a challenge compared to grassy types biofuels to feed. Ash deposition and boiler tube corrosion can be an issue for some cofiring arrangements depending on biomass and coal chemistry and operating conditions. Biomass can contain considerable alkali and alkaline-earth elements and chlorine which, when mixed with other gas components derived from coal such as sulfur compounds, promotes a different of array of vapor and fine particulate deposition in a coal-fired boiler (8, 9, 23).

The focus of the work performed in this project is primarily related to wood- and wheat straw-derived waste biomass by-products and their effect on ash deposition and corrosion during combustion.

4.0 SCOPE OF WORK

Samples of medium-density fiberboard (MDF, a wood product) and wheat straw board were shipped to the EERC for use in fouling and corrosion tests. The samples were ground and submitted for proximate, ultimate, heating value, and bulk ash composition analyses. Advanced analyses using computer-controlled scanning electron microscopy (CCSEM) and chemical fractionation were also performed. Fouling tests were performed in the EERC’s combustion and environmental process simulator (CEPS) test facility. The baseline MDF and blends of 95–5, 90–10, and 80–20 MDF–wheat straw were tested for fouling propensity and deposit strength development. During these tests, fly ash samples were collected for use in laboratory tests of corrosion.

Corrosion testing of the fly ash produced for the baseline and blends consisted of preparing small coupons of three candidate metals (a carbon steel, a stainless steel, and Hastelloy alloy, all provided by Sauder). Approximately 1 gram of the fly ash generated in fouling tests was mounted on these metal coupons and placed in a muffle furnace for durations of 500 and 1000 hours. In all, four fly ash samples and three metal samples were used in a test matrix of two durations and two temperatures (750° and 1100°F) to study the corrosive effects of the various fly ash samples on each metal.

Advanced analyses on each fuel will be used as input for modeling efforts to look at the effects of blends containing wheat straw on high-temperature fouling, low-temperature fouling, opacity, furnace wall slagging, and sootblower effectiveness (deposit strength). Because the model was developed to distinguish expected behavior between various coal types, the indices may require modification for applications with biomass, particularly with the wheat straw board. Test results will be used to establish any differences existing between biomass ash fouling and coal ash fouling.

5.0 FUEL ANALYSIS AND RESULTS

Samples of each fuel were submitted for standard American Society for Testing and Materials (ASTM) analyses, proximate, ultimate, heating value, and bulk ash chemistry and advanced analyses using CCSEM and chemical fractionation.

CCSEM analysis quantifies the different mineral species in a fuel such as coal fairly rigorously and also determines the size distribution of the minerals. Two fuels can have similar bulk elemental compositions but widely differing mineral contents. Specific mineral phases present are inferred from ranges of chemical composition for each particle size range. Particles not falling into these criteria are classified as "unknown." SEM image analysis is used in conjunction with the CCSEM data to determine whether discrete minerals are locked within individual coal particles or liberated as free mineral particles (i.e., included or excluded) from fuel particles. However, the CCSEM technique does not analyze inorganics that are atomically dispersed in the coal organic matrix. These inorganics are commonly termed organically bound minerals, the content of which is determined by chemical fractionation.

The chemical fractionation technique uses a series of leaching steps to determine the association of the inorganics in the fuel matrix. The extraction steps with water and ammonium acetate remove water-soluble material such as sodium chloride and organically bound cations such as the salts of carboxylic acids, respectively. Hydrochloric acid extraction removes more refractory inorganic species such as calcium carbonates. The inorganic species that are not extracted during the procedure are usually present as quartz, clay minerals, or metallic oxides in the fuel. Since silicon is present as quartz or as aluminosilicate clay which cannot be extracted in this procedure, the results are usually normalized to zero percent silicon loss.

The nature of the biomass fuels resulted in several difficulties which needed to be resolved during the course of the chemical fractionation and CCSEM analyses. The chemical fractionation analyses were complicated by the small amount of ash present and the presence of significant amorphous soluble silica. To obtain more accurate results with the small quantities of ash present, elemental concentrations were determined by inductively coupled atomic emission spectroscopy of the analytes rather than x-ray fluorescence (XRF) analysis of the remaining extracted ash as is done with coals. The chemical fractionation results were also not normalized to 0% silicon loss. The CCSEM analyses involved finding a suitable means of sample preparation, since the normal epoxy or wax mounting and polishing method for coals proved unworkable for the biomass samples. A satisfactory method was found to consist of preparing a densely compressed pellet of the material similar to that used to prepare XRF sample pellets. The successful preparation process consists of mixing 2 grams of the biomass material with 2 mL of collodion diluted with acetone. The sample is then dried in a vacuum oven at 60°C for 4 hours to remove the acetone. The sample is pressed into a pellet using cellulose as a backing under 3200 psi pressure. The process produces a very flat, smooth surface suitable for carbon coating and SEM analysis. The CCSEM analyses of biomass also showed that some parameters reported for coals, such as the percentage of epoxy, were not appropriate for these materials. The presence of highly irregular plant-derived inorganic components such as amorphous silica sheets shown in Figure 2 may also result in misleading particle-size distributions.

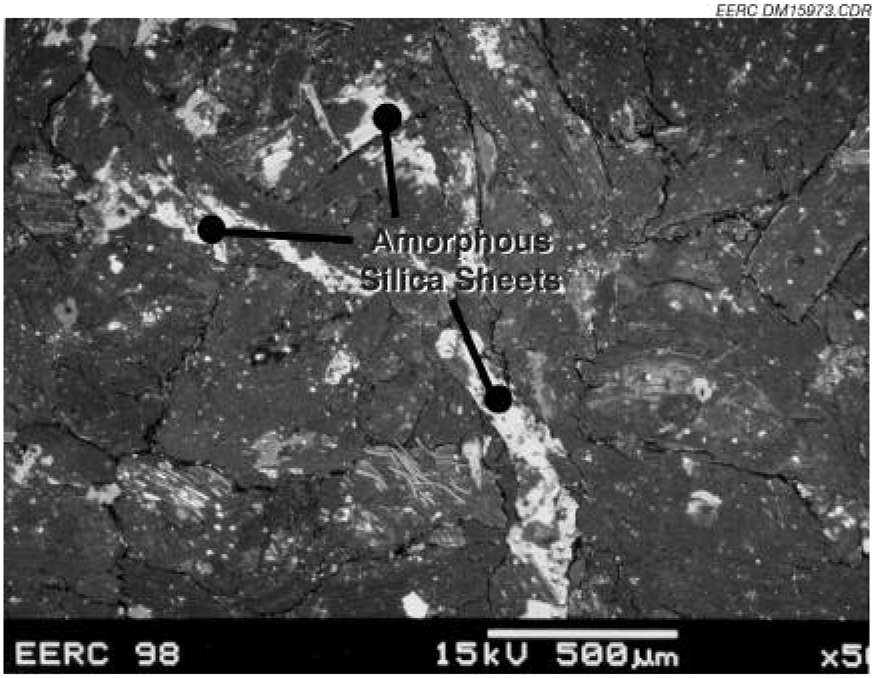

Figure 2. SEM image of wheat straw showing irregular amorphous silica sheets.

Analytical results for the ASTM analyses are presented in Table 1. The MDF is a low-moisture-content (5.8%), low-ash-content (0.58%) fuel with an as-received heating value of 7690 Btu/lb. The wheat straw board contains similar moisture content (6.70%), slightly lower heat content (6905 Btu/lb), and significantly higher ash content (7.83%). Chlorine content was measured at 760 and 2620 ppm for the MDF and wheat straw, respectively. Bulk ash composition for the wheat straw indicated an extremely high concentration of silicon dioxide at 71.0% of the ash. The majority of all other species were alkaline: 4.0% CaO, 3.3% MgO, 1.1% Na_2O, and 12.4% K_2O. Initial morphological examination of the minerals in the wheat straw indicated that the silica was present as a thin, amorphous coating on the straw fibers, which is very different from the quartz grains normally associated with fuels such as coal.

The results of the chemical fractionation analyses of the fuels are given in Table 2. To improve accuracy, analyses were performed using inductively coupled plasma emission spectroscopy rather than XRF analysis, because of the small amount of residual ash present. For both fuels, a significant portion of all elements except aluminum are extracted by the water and ammonium acetate. This includes 23% of the silica in the wheat straw and 30% of the silica in the MDF. In coals, extraction by water and ammonium acetate is indicative of highly dispersedorganically bound cations. However, in the biomass samples, this extract ability may simply indicate significant solubility of discrete inorganic structures in the plant material.

Results for advanced analyses using CCSEM are not available at this time.

TABLE 1

ASTM Analyses of the Fuels

	MDF	Wheat Straw Board
Proximate Analysis, wt%		
Moisture	5.80	6.70
Volatile Matter	83.19	72.73
Fixed Carbon	10.43	12.74
Ash	0.58	7.83
Ultimate Analysis, wt%		
Hydrogen	5.79	5.65
Carbon	43.44	40.77
Nitrogen	3.93	1.24
Sulfur	0.10	0.15
Oxygen	46.15	44.36
Ash	0.58	7.83
Chlorine, ppm	760	2620
High Heating Value, Btu/lb	7690	6905
Ash Analysis, wt% of Ash		
SiO_2	32.90	71.00
Al_2O_3	3.51	0.30
Fe_2O_3	4.42	0.50
TiO_2	0.30	0.10
P_2O_5	3.11	2.70
CaO	32.97	4.00
MgO	5.03	3.30
Na_2O	9.45	1.10
K_2O	5.33	12.40
SO_3	3.00	4.50

6.0 COMBUSTION TESTING AND RESULTS

The conversion and environmental process simulator (CEPS) is shown in Figure 3. The CEPS is a downfired furnace with a firing rate equal to about 4.0 lb/hr (1.8 kg/hr) of pulverized coal or 1.5 lb/hr oil with a heat output of approximately 30,000 Btu/hr. The electrically heated 12-ft vertical radiant furnace portion has an inside diameter of 6 in. for the first 9 ft, with the final heated section diameter reduced to 3 in. The radiant zone exit is through a horizontal 1.5-in.-inside-diameter ceramic tube. Acute control of gas temperatures and composition throughout the CEPS furnace is possible independent of the heat content of the fuel because of the external heating capability. Heating elements line the main furnace, convective pass section, and baghouse chambers. Temperatures of the flue gas (approximately 5–10 scfm) can attain a maximum of 1500°–1600°C (2732°–2912°F) in the radiant section and can be maintained at 760°–1200°C (1400°–2200°F) in the convective pass section and 120°–250°C (248°–482°F) in the baghouse, with the capability to go higher. There is ample access for sampling, observation,

TABLE 2

Chemical Fractionation Analyses of the Fuels

MDF Sample

Element	Initial (ppm oxide)	% Removed by Water	% Removed by NH_4OAc	% Removed by HCl	% Remaining
Silica	3426	13	17	0	70
Aluminum	365	0	0	0	100
Iron	460	0	44	39	17
Titanium	31	6	0	18	76
Phosphorus	323	56	32	8	5
Calcium	3433	9	75	15	1
Magnesium	524	33	64	1	2
Sodium	984	81	17	0	2
Potassium	555	70	26	0	4
% Total Ash		22.8	59.4	3	14.9

Wheat Straw Sample

Element	Initial (ppm oxide)	% Removed by Water	% Removed by NH_4OAc	% Removed by HCl	% Remaining
Silicon	51198	6	17	0	77
Aluminum	0	0	0	0	100
Iron	638	37	9	54	0
Titanium	64	22	0	18	60
Phosphorus	2090	46	40	11	3
Calcium	2582	4	87	9	0
Magnesium	3010	13	71	1	15
Sodium	819	60	40	0	0
Potassium	9224	28	70	1	1
% Total Ash		10.1	36.3	0	53.6

and optical diagnostics through access ports located throughout the CEPS. A PC displays and records temperatures, gas flows, feed rates, and flue gas compositions. Flue gas (O_2, CO_2, CO, SO_2, and NO_x) compositions are sampled from ports in the radiant section and after the collection device.

Combustion test samples were prepared for CEPS evaluation by preparing weight percentage blends from milled parent fuels. A wood chipper with a fine screen was used to prepare the samples prior to blending. The overall size distribution of each fuel was larger than that normally associated with wood wastes at Sauder’s manufacturing plant. Dry sieve analyses of each sample were performed and compared with the size of a sample of wood waste provided by Sauder and are shown in Table 3. Although much coarser than the wastes at Sauder, samples were fine enough to feed in the CEPS combustor.

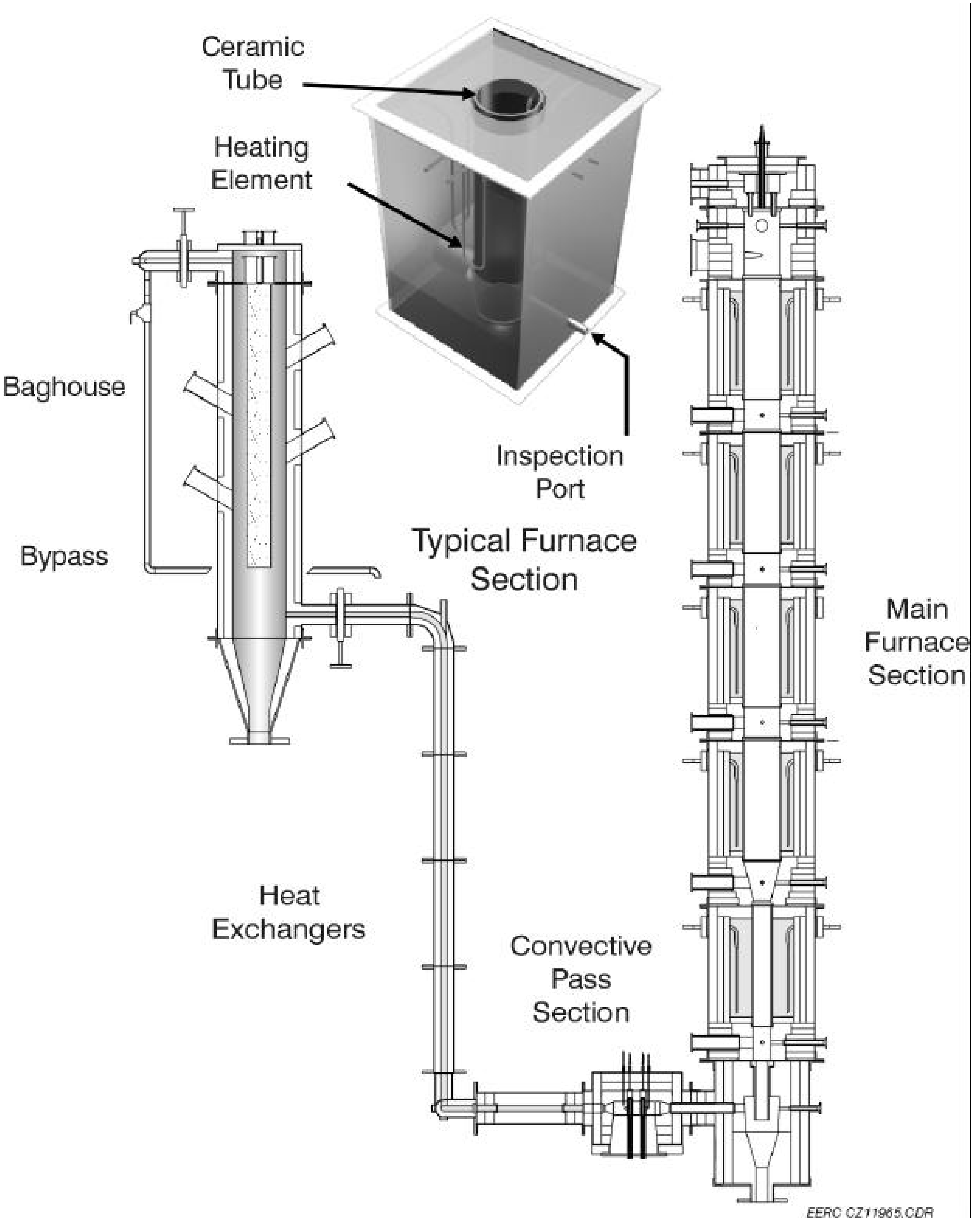

Figure 3. Design sketch of the conversion and environmental process (CEPS) showing the main furnace and convective pass section, heat exchangers, and baghouse.

TABLE 3

Dry Sieve Analysis of the Fuels

Sieve Screen, mesh	Sauder Sawdust	MDF Grind	Wheat Straw Grind
18		12.2	7.9
20	3.6	12.0	13.5
30	5.5	23.5	26.2
40	8.2		
60	13.3	27.4	33.5
100	15.7	9.1	10.2
140	9.3	4.5	3.5
170	13.5		
200	10.0		
270	4.3		
Pan	16.5	11.3	5.1

The baseline MDF and three blends of MDF containing 5%, 10%, and 20% wheat straw board were fired in the CEPS combustor to determine ash-fouling characteristics for each fuel. The coarse size distribution of these fuels created some difficulty in achieving 100% carbon burnout, with many sparklers entering the region of the test furnace where deposits were collected. Discussions with Sauder personnel indicated that normal boiler operation has good carbon burnout; however, sparklers are continuously seen entering the convective region of the boiler. Operating parameters for the baseline MDF included cooling the deposit probe metal surface to a temperature of 750°F with air. Gas temperatures in the deposit region were maintained near 2200°F. Visual observation of the deposit indicated very slow growth under these conditions, with minimal sintering. Because the furnace exit gas temperature of the boiler was unknown, it was assumed that, perhaps, higher temperatures than those implemented here existed at the furnace exit of the Sauder boiler. In an effort to establish sintering behavior for this fly ash, both the gas temperature and surface metal temperature were increased to 2550° and 1000°F, respectively. Again, no considerable deposit was formed over an 8-hour time period. These results indicate a low fouling propensity for the baseline MDF waste. The results of fouling tests are presented in Table 4.

A photograph of the baseline deposit can be seen in Figure 4. Plant operations have indicated that this fuel builds large deposits, albeit over long time periods, requiring manual steam cleaning of heat-transfer surfaces. Examination of the baseline MDF deposit indicated a hard surface coating, believed to be the precursor to a more significant deposit. The low ash content of the MDF is the primary contributor to the low growth rate observed. The fused nature of the base coating indicates that a portion of the fly ash is molten in the convective region of the boiler and that significant deposits may build over long time periods if left unchecked with no cleaning of surfaces.

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Figure 4. Baseline MDF wood deposit.

TABLE 4

Fouling Test Results

Run No.:	62	63	64	65	66	67	68
Fuel Description	MDF	MDF	MDF	80–20 blend	80–20 blend	90–10 blend	95–5 blend
Total Fuel, g	3910	4042	3438	5239	1624	4232	3974
Ash Content, %	0.58	0.58	0.58	2.03	2.03	1.31	0.94
Ash Fed, g	22.68	23.44	19.94	106.35	32.97	55.44	37.36
Deposit Weight, g	0.80	0.83	0.55	2.07	1.48	1.78	0.42
Duration, hr	4.70	5.90	3.73	2.57	1.87	4.55	4.50
Deposition Rate, g/hr	0.17	0.14	0.15	0.81	0.79	0.39	0.09
Probe Surface Temp., °F	1022	752	752	1022	752	752	752
Gas Temp., °F	2192	2192	2552	2552	2192	2192	2192
Physical Description	No slag	No slag	No slag	Slag	Slag	Slag	No slag

The next series of tests were performed on the 80–20 MDF–wheat straw blend, potentially the highest blend ratio considered at the plant. Initial operating characteristics included high gas temperature and high surface metal temperature, similar to those used for the baseline MDF. Results were quite dramatic, as a completely sintered deposit of considerable size was formed over a 2.5-hour test period. The deposit was a black, molten slag covering the exposed portion of the deposit probe on its upstream side, as seen in Figure 5. The higher ash percentage in the blend (2.03% versus 0.58% for the baseline MDF) contributed to the increased deposit size. However, the molten nature of the deposit indicated a very high fouling potential for this blend. Because the operating conditions were more severe than those of the initial baseline test, the gas temperature and probe metal temperature were lowered to 2200° and 750°F, respectively. Again, a highly sintered ash deposit was formed over a 1.5-hour test period, confirming the high fouling potential noted in the previous test of the 80–20 blend. Deposits of this nature are almost certain to require immediate removal from boiler tube surfaces to prevent the deposit from bridging between tube banks and blocking convective passages. Because cleaning is performed manually at the Sauder boiler, this represents an impractical situation.

Similar deposit characteristics were noted for the 90–10 MDF–wheat straw blend, although the lower ash content of the blend (1.31%) required a test period of 5.2 hours to achieve similar deposit size, as shown in Figure 6. Again the deposit was heavily sintered, but did not completely incorporate all depositing fly ash grains into a homogeneous deposit matrix, as seen in the 80–20 blend. The high percentage of molten particles on the deposit surface also indicates a high fouling potential for this blend. The 95–5 MDF–wheat straw blend exhibited lower fouling

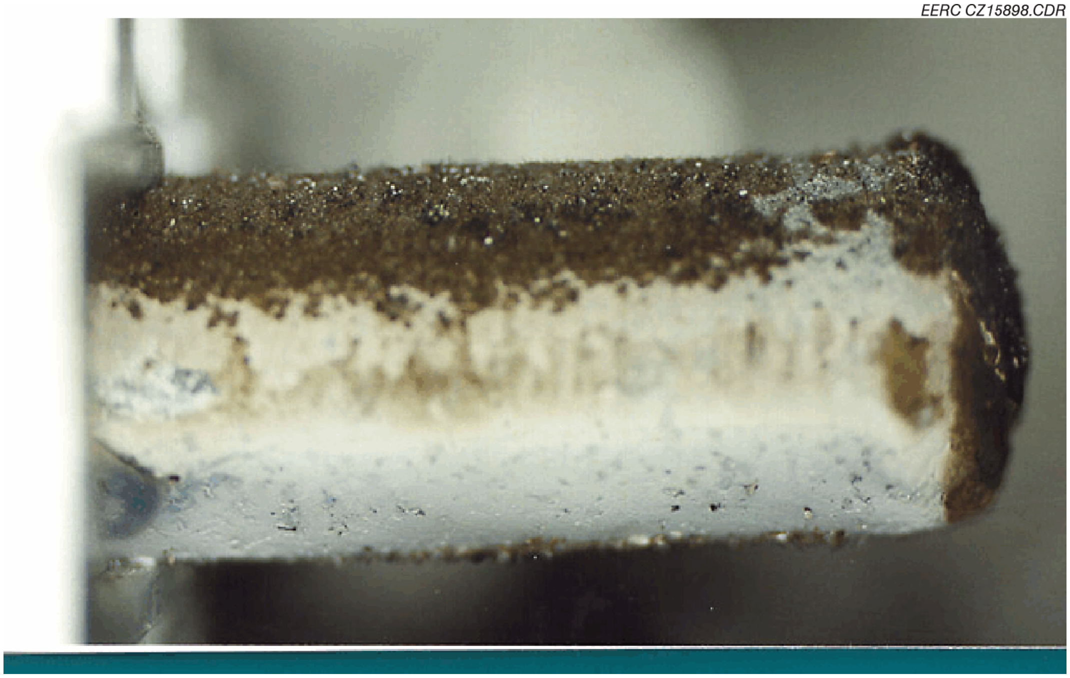

Figure 5. 80% MDF wood–20% wheat straw deposit.

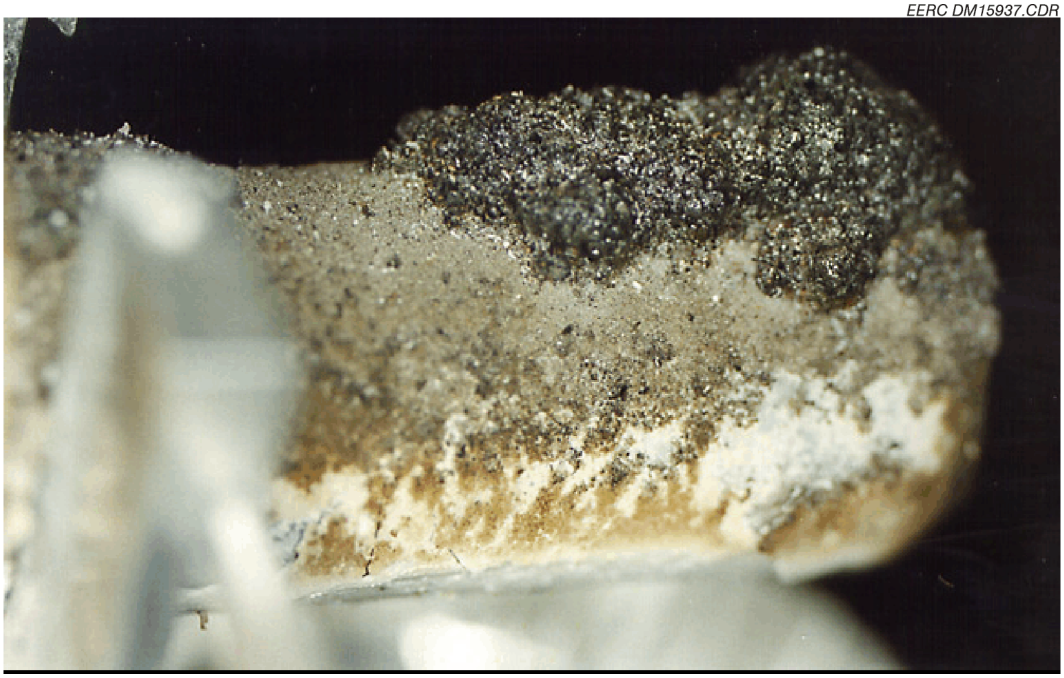

Figure 6. 90% MDF wood–10% wheat straw deposit.

potential than either of the blends containing a higher percentage of wheat straw. However, molten ash can be seen on the deposit surface in Figure 7.

The deposits were submitted for advanced mineralogical and morphological examination using scanning electron microscopy point count (SEMPC) techniques. Mineral species identified in the deposits are given in Table 5 and the bulk deposit chemistry in Table 6. The 100% MDF wood ash deposit composition is dominated by calcium oxide, mixed calcium oxides, and calcite species, with significant sulfur capture as mixed calcium sulfate material. The 95% MDF–5% wheat straw deposit shows a marked decrease in the amounts of calcium-based species as a result of blending with the high-ash-content, low-calcium-content wheat straw. Significant sulfur capture still occurs at this blend level. There is also an increase in the amount of silica and mixed silica-rich species. The 90% MDF–10% wheat straw and 80% MDF–20% wheat straw deposits are predominantly comprised of quartz and mixed silicate species. The trend toward increased silicate and decreased calcium species is also seen in the bulk ash chemistry of the deposits. The amount of potassium in the deposits also increases significantly as the percentage of straw in the blend is increased. The predominance of mixed silicate material containing significant potassium is conducive to forming sintered, sticky deposits leading to problematic convective pass fouling.

Overall, the addition of wheat straw waste in blend with MDF wastes leads to increased deposition and problematic deposit properties. The deposition rate is directly proportional to the percentage of wheat straw in the blend, because of the composition and the increased ash content. Because the wheat straw minerals tend to form molten fly ash grains under normal boiler operating parameters, deposit strength is predicted to be similarly high for all mature deposits.

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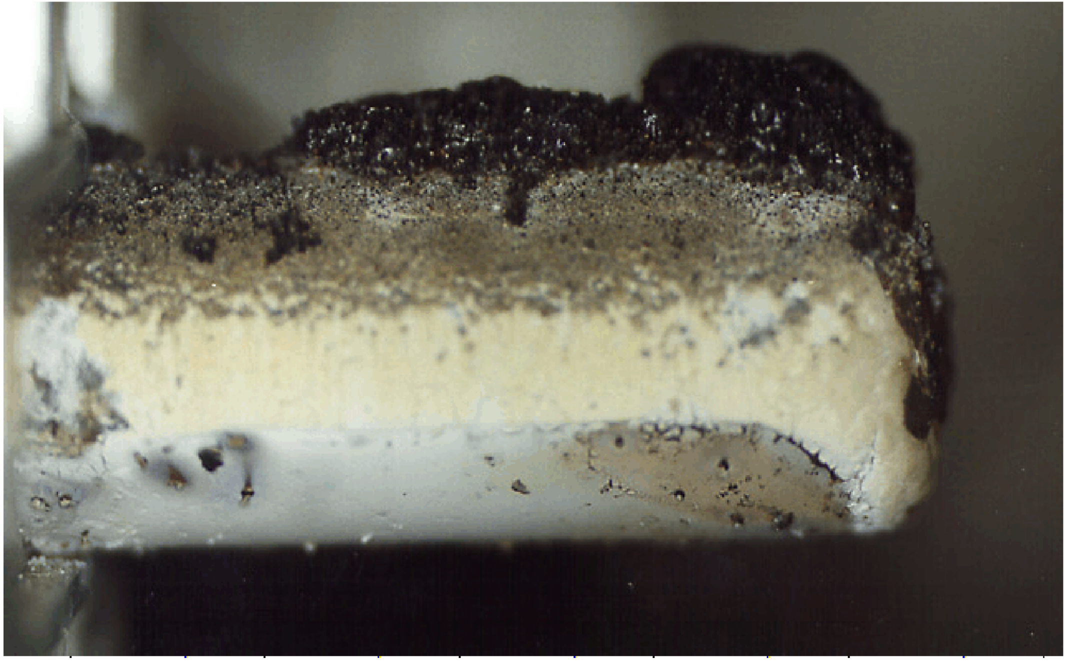

Figure 7. 95% MDF wood–5% wheat straw deposit.

Molten fly ash grains have a sticky surface that will attach to metal heat-transfer surfaces and form a bond with that surface. Once a bond is formed, the deposit becomes increasingly difficult to remove. The extent to which these deposits are problematic will be related to both the growth rate and the effectiveness of manual cleaning in removing them from metal surfaces. It is likely that all blends containing wheat straw, even at 5%, will eventually lead to problematic deposition in the Sauder boiler.

7.0 CORROSION TESTING AND RESULTS

Coupons were prepared from samples of carbon steel, stainless steel, and a Hastelloy steel alloy provided by Sauder. The test conditions for the corrosion testing were chosen to simulate the fouling-zone steam temperature, flue gas composition, and contact of tube surface with deposited ash in a full-scale boiler. The corrosion experiments are, of course, a simplified simulation, with other factors such as alkali vapor equilibrium not considered. The corrosion rates obtained are indicative of the relative resistance of the metals tested to this environment and may not reflect actual corrosion rates observed in a full-scale boiler. As described in the work scope, fly ash collected during fouling tests was mounted on these samples and inserted in a muffle furnace at temperatures of 750° and 1100°F for durations of 500 and 1000 hours. Samples of the three alloys were cut into coupons roughly 1.3 cm by 1 cm and cleaned by sonicating in acetone for 5 minutes. All samples were marked with a metal stamp set for easy indentification after the test. Samples for mass loss calculations were weighed and their surface areas calculated before the

TABLE 5

Deposit Mineral Species Identified by SEMPC

UND EERC Mineral Classification				
Mineral Name	100% Wood Ash Deposit, frequency %	95% Wood Ash–5% Wheat Straw, frequency %	90% Wood Ash–10% Wheat Straw, frequency %	80% Wood Ash–20% Wheat Straw, frequency %
Oxide-Rich				
Calcium Oxide	24.1	2.2	0.0	1.8
Titanium Oxide	0.0	0.0	0.0	0.7
Iron Oxide	0.0	1.1	0.0	0.0
Mixed Oxide-Rich	10.4	15.9	0.9	2.5
Total for Group	34.4	19.3	0.9	5.0
Sulfur-Rich				
Pyrite	0.4	0.0	0.0	0.0
Calcium Sulfate	0.0	0.4	0.0	0.0
Na–Ca Sulfate	3.3	0.4	0.0	0.0
Mixed Sulfur-Rich	15.9	15.6	0.5	1.4
Total for Group	19.6	16.3	0.5	1.4
Phosphorus-Rich				
Apatite	0.0	0.0	0.5	0.0
Mixed Phosphorus-Rich	1.9	0.4	0.5	2.1
Total for Group	1.9	0.4	0.9	2.1
Carbon-Rich				
Calcite	14.4	4.4	0.9	0.7
Altered Calcite	2.2	1.5	0.5	0.0
Dolomite	0.7	0.0	0.5	0.0
Mixed Carbon-Rich	0.7	4.8	0.0	0.0

Continued . . .

TABLE 5 (continued)

	UND EERC Mineral Classification			
Mineral Name	100% Wood Ash Deposit, frequency %	95% Wood Ash–5% Wheat Straw, frequency %	90% Wood Ash–10% Wheat Straw, frequency %	80% Wood Ash–20% Wheat Straw, frequency %
Total for Group	18.1	10.7	1.8	0.7
Metal Rich				
Mixed Metal-Rich	0.0	3.0	0.5	0.4
Total for Group	0.0	3.0	0.5	0.4
Silicon-Rich				
Quartz	1.5	11.5	3.6	17.4
Leucite	0.0	0.0	0.5	0.0
Illite	0.0	1.1	0.9	0.4
Pyroxene	0.4	2.6	9.5	8.9
Wollastonite	0.0	0.0	0.0	1.1
Ca Silicate	0.0	0.0	2.3	4.6
Di Calcium Silicate	2.6	0.0	0.5	2.1
$NaCaSiO_3$	0.7	0.0	0.0	0.0
Akermanite	0.0	0.0	0.9	0.0
Spurrite	1.1	0.0	0.0	0.0
Mixed Silicon-Rich	7.0	24.8	77.3	53.7
Total for Group	13.3	40.0	95.5	88.3
Total Number of Points Analyzed	270	270	220	281
Carbon Threshold Value	2000	2000	1000	2000
Oxygen Threshold Value	300	300	150	300

TABLE 6

Deposit Bulk Ash Chemistry

Cumulative Bulk Chemical Composition Summary

	100% Wood Ash Deposit Total Sample	95% Wood Ash– 5% Wheat Straw Total Sample	90% Wood Ash– 10% Wheat Straw Total Sample	80% Wood Ash– 20% Wheat Straw Total Sample
SiO_2	9.4	30.7	65.5	62.4
Al_2O_3	1.4	0.9	0.6	0.8
Fe_2O_3	1.0	2.0	1.0	0.7
TiO_2	0.1	0.1	0.1	3.7
P_2O_5	3.9	2.3	1.4	2.7
CaO	55.0	20.2	15.4	16.3
MgO	5.1	3.8	3.7	3.0
Na_2O	3.8	2.1	1.2	0.7
K_2O	2.3	15.1	9.9	7.8
SO_3	15.6	9.2	0.6	1.3
ClO	1.2	13.2	0.1	0.2
Cr_2O_3	0.2	0.1	0.2	0.1
BaO	0.8	0.3	0.2	0.2
Points	270	270	220	281

test. Ashes of 100%, 95%, 90%, and 80% MDF were placed on the coupons and arranged into four sets as shown in the table below. These coupons were then placed in a ceramic furnace which has programmable heating zones. This allowed all coupons to be tested at the same time even though the testing temperatures were different. A synthetic combustion gas composed of 14% carbon dioxide, 4% oxygen, 1000 ppm sulfur dioxide, and the balance nitrogen was introduced into the furnace at a flow rate of 0.5 scfh. This gas composition is similar to that measured in the CEPS tests and corresponds to that expected in full-scale combustion systems. Sample sets were removed after 500 hours and 1000 hours, half were weighed for mass loss calculations, and half mounted in epoxy and polished for SEM examination.

Samples removed for the mass loss calculations were cleaned as described in ASTM Procedure G1-88, Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens. These coupons were cleaned to remove any corrosion products before weighing. Corrosion rates were calculated using the formula given in Procedure G1-88. The results of the corrosion tests are given in Table 7.

These results from corrosion tests indicated similarly increasing wastage of each metal with increasing percentage of wheat straw board in the blend. As expected, corrosion was also shown to be temperature-dependent, as the samples maintained at 750°F showed generally lower corrosion rates than their 1100°F counterparts. Of the three metal samples used, the carbon steel suffered the greatest corrosion, with significant wastage observed over all test conditions. The Hastelloy indicated the best resistance to corrosion, with minimal wastage at the low temperature and slightly greater wastage at the higher temperature. The stainless steel also had significantly better corrosion resistance than the carbon steel, with slightly less resistance than the Hastelloy. The corrosion tests will provide baseline data for possible future modifications to PCQUEST, possibly allowing for prediction of corrosion potential of a given fuel, particularly high-chlorine-content fuels such as wheat straw.

SEM examination of the carbon steel samples showed a highly irregular surface. All samples formed an iron oxide layer, which in some areas was as thick as 0.2 mils (5 microns). The surface was also subjected to excessive pitting. At the interface of the oxide layer and metal, sulfur was detected in all samples in amounts ranging from 2.5% to 5%. The presence of sulfur produces areas of localized reducing conditions which promote corrosion. Intergranular attack could be observed in the samples as deep as 0.4 to 0.8 mils (10 to 20 microns) from the oxide layer. The resulting materials between grains were oxides rich in iron and chromium with some minor amounts of sulfur. Intergranular attack increased with the *decrease* in MDF% and *increase* in temperature.

Examination of the stainless steel displayed a smoother surface than the carbon steel, with only minor pitting. Maximum depths of these pits were less than 0.04 mils (1 micron). Intergranular attack could not be detected on samples analyzed. No oxide layer could be detected.

TABLE 7

Corrosion Test Results

Carbon Steel

Temperature		Hours	Wastage (mils/year), % MDF				Wastage (mm/year), % MDF			
°F	°C		100	95	90	80	100	95	90	80
750	399	500	1.356	2.242	2.204	2.005	0.0344	0.0569	0.0560	0.0509
750	399	1000	1.824	2.095	1.357	2.775	0.0463	0.0532	0.0344	0.0705
1100	593	500	3.891	2.095	4.280	4.161	0.0988	0.0532	0.1087	0.1056
1100	593	1000	10.139	3.202	3.550	7.083	0.2574	0.0813	0.0901	0.1799

Stainless Steel

Temperature		Hours	Wastage (mils/year), % MDF				Wastage (mm/year), % MDF			
°F	°C		100	95	90	80	100	95	90	80
750	399	500	0.039	0.000	0.000	0.000	0.0010	0.0000	0.0000	0.0000
750	399	1000	0.027	0.038	0.039	0.026	0.0007	0.0010	0.0010	0.0007
1100	593	500	0.000	0.209	0.119	0.131	0.0000	0.0053	0.0028	0.0033
1100	593	1000	0.019	0.514	0.097	0.038	0.0005	0.0130	0.0025	0.0010

Hastelloy Alloy

Temperature		Hours	Wastage (mils/year), % MDF				Wastage (mm/year), % MDF			
°F	°C		100	95	90	80	100	95	90	80
750	399	500	0.000	0.000	0.000	0.000	0.0000	0.0000	0.0000	0.0000
750	399	1000	0.043	0.048	0.033	0.038	0.0011	0.0012	0.0009	0.0010
1100	593	500	0.111	0.111	0.142	0.174	0.0028	0.0028	0.0036	0.0044
1100	593	1000	0.026	0.032	0.009	0.048	0.0007	0.0008	0.0002	0.0012

Thus far, SEM analysis of all the samples for 500 hours for the carbon steel have been completed along with half of the samples for the stainless steel and Hastelloy alloy. The samples from the 1000-hour tests are being prepared for analysis.

8.0 PREDICTIVE MODELING

No results from the predictive modeling are yet available pending the completion of the CCSEM analyses.

9.0 CONCLUSIONS AND RECOMMENDATIONS

All blends containing wheat straw will exhibit increased fouling relative to the baseline MDF. The best candidate blend ratio for wheat straw waste firing in the existing Sauder boiler is the 95–5 MDF–wheat straw blend. Fouling and deposit strength are both expected to be greater than the baseline MDF waste but may be manageable, with an expected increase in sootblowing. Blends containing higher percentages of wheat straw board waste are not recommended because of expected formation of problematic deposits of high strength that may lead to blocking of convective passages.

It is recommended that expansion of the boiler plant consider a fluid-bed combustor for burning wood wastes. The lower operating temperatures of the fluid-bed system should significantly reduce ash-fouling tendencies for these fuels. Because of the high alkaline content of the wheat straw board, additional testing may be required to determine the extent of problematic clinker formation in the bed. A fluid bed installation should consider an automatic tramp removal system to allow for complete flexibility with respect to fuel blends, particularly high-alkaline-content fuels.

Results from corrosion tests indicated similarly increasing wastage of each metal with increasing percentage of wheat straw board in the blend. As expected, corrosion was also shown to be temperature-dependent, as the samples maintained at 750°F showed lower corrosion than their 1100°F counterparts. Of the three metal samples used, the carbon steel suffered the greatest corrosion, with significant wastage observed over all test conditions. The Hastelloy indicated the best resistance to corrosion, with minimal wastage at the low temperature and slightly greater wastage at the higher temperature. The stainless steel also had significantly better corrosion resistance than the carbon steel, with slightly less resistance than the Hastelloy. The corrosion test will provide baseline data for possible future modifications to PCQUEST, possibly allowing for prediction of corrosion potential of a given fuel, particularly high-chlorine-content fuels such as wheat straw.

Advanced analyses on each fuel will be used as input for PCQUEST modeling to examine the effects of blends containing wheat straw on high-temperature fouling, low-temperature fouling, opacity, furnace wall slagging, and sootblower effectiveness (deposit strength). Because the model was developed to distinguish expected behavior between various coal types, the indices may require modification for applications with biomass, particularly with the wheat straw board. Test results will be used to establish the differences existing (if any) between biomass ash fouling and coal ash fouling. This project is continuing under the new cooperative agreement, and the PCQUEST modeling results will be included in a second final report to be submitted when the project is completed.

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