

PILOT SCALE PRODUCTION AND COMBUSTION OF LIQUID FUELS FROM REFUSE DERIVED FUEL (RDF) - PART II

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ABSTRACT

EnerTech is developing a process for producing pumpable slurry fuels, comparable to Coal-Water-Fuels (CWF), from solid Refuse Derived Fuels (RDF). Previous reports (Klosky, April 1995 and Klosky, October 1995) have described the characteristics of the enhanced carbonized RDF slurry fuels. This paper summarizes those fuel characteristics and reports on the latest combustion tests performed with the final product fuel.

The objective of this research was to determine the boiler and emission performance from the carbonized RDF slurry fuel using statistical screening experiments. Eight combustion tests were performed with a pilot scale pulverized coal/oil boiler simulator, with CO, SO₂, and NO_x emissions determined on-line. The combustion tests produced simultaneous CO and NO_x emissions well below and SO₂ emissions comparable to the promulgated New Source Performance Standards (NSPS). This research will form the basis for later combustion experiments to be performed with the carbonized RDF slurry fuel, in which dioxin/furan and trace metal emissions will be determined.

INTRODUCTION

In 1993, the U.S. generated approximately 207 million tons of Municipal Solid Waste (MSW), with 62% landfilled, 22% recycled, and 16% processed through Municipal Waste Combustion (MWC) (EPA 1994). In order to divert a larger portion of this generated MSW from landfills, MWC will have to play a growing role in MSW disposal. However, recently promulgated NSPS (EPA, October 1995) will add an additional financial burden, through mandated emission reductions and air pollution control technologies, to an already financially troubled MWC industry.

In the past, RDF, a solid fuel produced from MSW, has been fired in coal boilers as an alternative means of MWC. While lower sulfur dioxide (SO₂) emissions provided the impetus, firing RDF in coal

boilers suffered from several disadvantages including increased solids handling, increased excess air requirements, increased air emissions, increased slag formation in the boiler, and higher fly ash resistivity.

Bituminous and higher rank coals can generally be slurried to pumpable fuels of satisfactory solids loading, and hence heating value. These slurry fuels, sometimes termed Coal-Water-Mixtures (CWM) or CWF, have been and still are commercially fired in pulverized coal (pc-) and oil boilers. However, low rank solid fuels, like RDF, do not slurry as well. Supported by the Department of Energy (DOE), Environmental Protection Agency (EPA), and National Science Foundation (NSF), EnerTech has developed a process called SlurryCarb™, which greatly improves the solids loading, heating value, chlorine content, and uniformity of RDF slurry fuels. The enhanced RDF slurry fuels can be effectively fired in pc- or oil boilers without the previously cited disadvantages.

With EnerTech's SlurryCarb™ process, a pumpable slurry of RDF is continuously pressurized with a pump between approximately 1200 and 2500 psi. The feed RDF slurry is pressurized above the saturated steam curve, in order to maintain a liquid state when the slurry is heated above its normal boiling point. From the pump, the pressurized slurry is heated by indirect heat exchange to approximately 480 to 660°F, with its pressure and temperature maintained for less than 30 minutes.

At this temperature and pressure, oxygen functional groups in structures of the RDF are split off as carbon dioxide gas. This removed carbon dioxide gas comprises a significant weight percentage of the feed RDF, but only a minimal percentage of the heating value. While the mass of total solids are reduced approximately 20-70%, the carbonized product still contains approximately 95-98% of the energy content of the feed RDF. The carbonized RDF particles are dramatically reduced in size and can be concentrated to a solids loading, and hence heating value,

comparable to CWM and CWF. In addition, chlorinated organics in the feed RDF are decomposed to hydrochloric acid, neutralized with alkalis, and removed as chloride salts, producing an essentially chlorine free carbonized RDF slurry fuel.

SUMMARY OF PREVIOUSLY REPORTED RESEARCH

EnerTech completed preliminary pilot scale SlurryCarb™ and combustion experiments with RDF in November 1994, with the results previously reported (Klosky, April 1995). In brief summary, preliminary experiments produced a homogeneous pumpable slurry fuel from RDF with a Higher Heating Value (HHV) up to approximately 6,600 Btu/lb (wet basis) at 51.7 wt.% total solids. The viscosity of this carbonized RDF slurry fuel was approximately 500 cP @ 100 Hz decreasing, and ambient temperature. Also, pilot scale slurry carbonization experiments extracted up to approximately 94% of the feed RDF chlorine content as chloride salts.

The RDF slurry fuel viscosity was determined based upon the yield power law equation for fluids. The viscosity was determined by shearing a slurry sample in the annular space between a rotating cylinder and a stationary cup. The torque necessary to rotate the cylinder at a given speed is measured by a torsion spring. In general, RDF slurry fuels are nonnewtonian fluids. With nonnewtonian fluids, the viscosity is dependent upon the shear rate and as a result, the rotating speed of the cylinder.

In addition, preliminary combustion experiments with the carbonized RDF slurry fuel, in a pc-oil boiler simulator, produced a carbon burnout exceeding 99.9%, with excess air as low as 15%. CO emissions averaged below 16 ppm (corrected to 7% O₂), while HCl and SO₂ emissions were below 17 and 40 ppm, respectively, without acid gas scrubbing. NO_x emissions depended on combustion temperature and averaged between 82-211 ppm without selective noncatalytic or catalytic reduction. In addition, mercury emissions were measured at 0.003 mg/dscm. Combustion ash was non-hazardous, with low leaching characteristics, based on a TCLP analysis.

This paper summarizes the latest data from combustion tests in a pc-oil boiler simulator with the carbonized RDF slurry fuel produced from the second round of slurry carbonization experiments.

RESEARCH PERFORMED

In June 1995, EnerTech completed a second round of SlurryCarb™ and combustion experiments with RDF (Klosky, October 1995). Prior to operation of the pilot plant, a larger reactor was added to the plant to potentially improve the characteristics of the carbonized RDF slurry from the previous research through longer residence times. In brief summary, carbonized RDF slurry fuels were produced up to approximately 6,400 Btu/lb (wet or slurry basis) at 49.7 wt.% solids, but at significantly reduced temperatures. At higher temperatures, slurry fuels up to 6,600 Btu/lb could be produced. In addition, the type and level of alkali added to the feed RDF slurry was modified during these experiments to improve chlorine extraction. Chlorine extractions over 98% were measured, a significant improvement.

RDF pellets from Thief River Falls, Minnesota have been used as the source material throughout EnerTech's experimental programs. This source of RDF was chosen due to its proximity to EnerTech's research facilities and chemical similarity to RDF produced with wet based resource recovery operations. The Thief River Falls Material Recovery Facility (MRF) receives mainly local MSW, some commercial office waste, and limited agricultural solid waste. The incoming waste is shredded and hand picked for glass bottles, aluminum cans, and PET and HDPE plastic bottles. The remaining waste is trommeled, air classified, subjected to magnetic separation, and finally pelletized. The RDF for the experimental programs was purchased as pellets from this MRF facility, and then shredded by EnerTech in a Nelmor granulator to a minus 1/8-inch particle size. It is roughly estimated that the RDF consists of approximately 60-70 wt.% paper, 15-20 wt.% plastics, and the balance "other" (dry basis).

The carbonized RDF slurry fuel was produced using the Energy & Environmental Research Center's (EERC) continuous 7.5 ton/day (wet basis) hot-water-drying pilot plant. A detailed description of this facility and its operation can be found in the previously cited papers by EnerTech (Klosky, April 1995 and Klosky, October 1995).

The combustion experiments with the carbonized RDF slurry fuel were performed in EERC's 650,000 Btu/hr Combustion Test Facility (CTF). The CTF (please see Figure 1) is a pc-oil combustion simulator. The combustion chamber is 30 inches in diameter, 8.2 feet high, and refractory lined. From a continuously stirred storage tank, the carbonized RDF slurry is pumped through the burner gun (please see Figure 2) to the atomizer, where it is mixed with atomizing air prior to entering the burner throat. Heated primary air carried the atomized slurry out of the burner gun, while heated secondary air is introduced in an annular section surrounding the burner gun. Heated tertiary air can be added through two tangential ports located in the furnace wall about 12 inches above the burner cone.

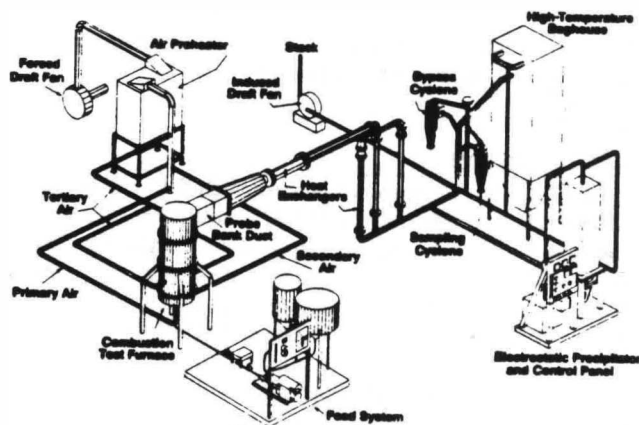


FIGURE 1 - SIMPLIFIED SCHEMATIC OF THE 650,000 BTU/HR PC-OIL COMBUSTION SIMULATOR.

Run No.	Feed Rate, lb/hr	Excess Air, %	Prim/Sec/Tert, %	Preheat Temp., °F	Swirl No.	Atomizing Air, scfm	CaO Addition, g/lb slurry
1	110	31	9/88/3	330	0.4	9.7	0.0
2	110	19	9/70/21	330	0.4	11.6	0.0
3	110	19	9/88/3	330	0.4	11.6	1.0
4	110	31	9/70/21	330	0.4	9.7	1.0
5	100	31	9/70/21	330	0.4	11.6	1.0
6	100	19	9/88/3	330	0.4	9.7	1.0
7	100	31	9/88/3	330	0.4	11.6	0.0
8	100	19	9/70/21	330	0.4	9.7	0.0

TABLE 1 - ACTUAL COMBUSTION SCREENING EXPERIMENT FACTORS WITH HIGH AND LOW LEVELS.

Flue gases pass out of the furnace into a 10 inch square duct that is also refractory lined. Located in the duct is a vertical probe bank designed to simulate superheater surfaces in the convective pass of a boiler. After leaving the test probe bank, flue gases pass through a series of water-cooled heat exchangers and then to an electrostatic precipitator (ESP) before being discharged.

For this combustion test, a statistical screening experiment was employed to determine the emissions and boiler performance under a variety of typical boiler conditions for the carbonized RDF slurry fuel. The designed screening experiment was based upon an "8-run" Plackett-Burman design. Table 1 summarizes the seven factors (sometimes called variables), with low and high levels (sometimes called set points).

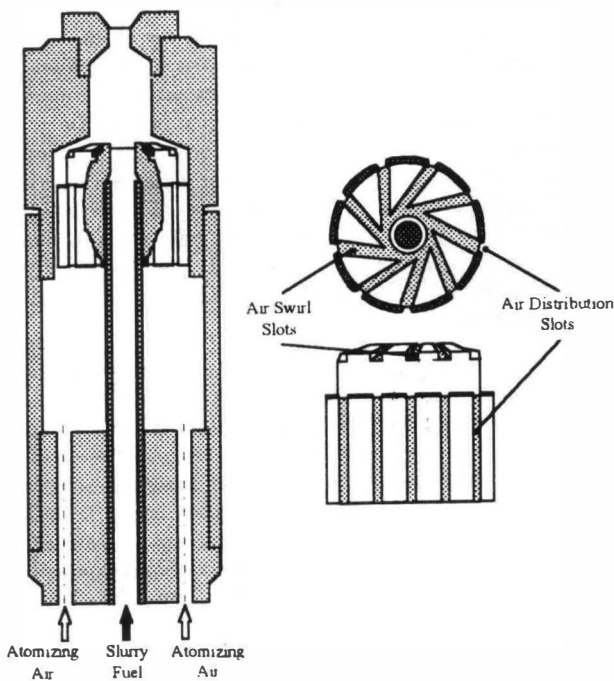


FIGURE 2 - SIMPLIFIED SCHEMATIC OF CARBONIZED RDF SLURRY FUEL BURNER GUN.

The Plackett-Burman screening experiment requires eight combustion runs for a seven factor design. Each combustion run lasted approximately 30 to 60 minutes. Samples of the carbonized RDF slurry were collected from each run and analyzed for heating value, rheology, ultimate analysis, and chlorine content. Moreover, samples of the collected fly ash were saved from each run and analyzed for carbon content. Also, combustion flue gases were continuously monitored for O₂, N₂, CO₂, CO, NO_x, and SO₂. A description of each factor is provided below.

1) Feed Rate - The feed rate of the carbonized RDF slurry fuel into the CTF was varied between 100 and 110 lb/hr (wet basis). The feed rate was controlled by the feed pump speed, with the pump head pressure held constant at approximately 100 psig.

2) Excess Air - The total amount of combustion air was varied between 19 and 31% excess. The stoichiometric amount of excess air was calculated based upon an ultimate analysis of the carbonized RDF slurry fuel. Total combustion air flow was controlled by an orifice valve on the CTF, and depended upon the carbonized RDF slurry fuel feed rate.

3) Prim/Sec/Tert - The total combustion air was divided between primary air, secondary swirl air, and tertiary overfire air. Primary air was left constant at 9% of total combustion air and only tertiary air was varied between 3 and 21% of total combustion air (and hence, secondary air, as the difference, was varied between 70 and 88%). Air flows were controlled by individual orifice valves on the primary, secondary, and tertiary air lines.

4) Preheat Temp. - The preheat temperature of the secondary and tertiary combustion air was to be varied between 330 and 700°F. However, due to slurry plugging problems, the preheat temperature for the secondary and tertiary air had to be held constant at 330°F. Since the secondary and tertiary air flows parallel to the burner gun in this combustor, the slurry water was being evaporated by the hot air at the nozzle tip causing the nozzle to plug. Primary air was not preheated and was held constant at approximately 100°F.

5) Swirl No. - The combustion tests were performed using a burner gun with an adjustable secondary air swirler. The swirl number was to be varied between 0.4 and 1.3, and is defined as the tangential momentum of the secondary air divided by the axial momentum of

the secondary air. However, the swirl number had to be held constant at 0.4. Due to the lower level of axial flowing air at the higher swirl setting, the carbonized RDF slurry fuel would not burn in suspension above the burner gun, but would drop out of suspension and accumulate on the bottom of the combustor.

6) Atomizing Air - The carbonized RDF slurry fuel is atomized with pressurized air at approximately 60 psig. Independent of primary air, secondary air, tertiary air, and feed rate, the volume of atomizing air was varied between 9.7 and 11.6 scfm. The volume of atomizing air is controlled through an orifice valve.

7) CaO Addition - Two distinct carbonized RDF slurry fuels were prepared and utilized for this combustion test. The first slurry fuel had approximately 1.0 grams of calcium oxide (CaO) per pound of carbonized RDF slurry blended with the fuel prior to the combustion test. The second carbonized RDF slurry fuel had no CaO added.

RESEARCH RESULTS

Table 2 summarizes the characteristics of the carbonized RDF slurry fuel, without the CaO added to the fuel. As summarized in previously cited papers (Klosky, April 1995 and Klosky, October 1995), the carbonized RDF slurry fuel used for this combustion test was a blend of several slurry fuels, produced under slightly different conditions in the slurry carbonization pilot plant.

	Thief River Falls, Mn. RDF	Carbonized Slurry Fuel w/o CaO
Ultimate, wt.%, m.f.		
Carbon	45.7	66.6
Hydrogen	5.6	7.9
Nitrogen	0.9	0.6
Sulfur	0.2	0.1
Oxygen (diff.)	39.2	11.1
Ash	8.4	13.7
Chlorine, µg/g, m.f.	3,000	172
Rheology		
Viscosity, cP	500	542
Solids Load., wt.%	9.1	49.5
High. Heating Value		
m.f., Btu/lb	7,995	12,860
Slurry, Btu/lb	730	6,370

TABLE 2 - FUEL PROPERTIES OF RAW AND CARBONIZED RDF.

Table 3 summarizes carbon monoxide (CO), sulfur dioxide (SO₂), and nitrogen oxides (NO_x) emissions from each run of the statistical screening combustion experiment. In addition, Table 3 includes the carbon content of the combustion ash from each run period.

The "main effect" of each factor from the combustion experiment was determined and compared to calculated control limits. Main effects which were outside of the control limits can

be considered a significant factor for that emission, and not just part of the common cause variation of the combustion test. Main effects were calculated by summing the high and low level responses separately, taking the difference between these two numbers, and dividing by the number of high levels (or low levels since they are equal). Control limits were calculated as twice the average standard deviation of each response. Statistical analysis of each major flue gas emission is presented below.

Run No.	CO (ppmv)	SO ₂ (ppmv)	NO _x (ppmv)	Ash Carbon (wt.%, m.f.)
1	1.4	43.7	132.1	1.04
2	1.5	43.0	134.5	1.21
3	3.2	42.4	198.4	0.01
4	0.1	57.4	224.3	0.40
5	0.6	57.2	174.0	0.51
6	3.3	52.4	139.0	1.09
7	0.1	42.3	153.6	0.50
8	2.0	49.9	124.8	1.27
NSPS	50-150	30	150	—

*All emission data have been corrected to 7% O₂ (dry basis).

TABLE 3 - EMISSION DATA FROM EACH RUN OF THE STATISTICAL SCREENING COMBUSTION EXPERIMENT.

Carbon Monoxide (CO)

The CO emissions from all eight runs were extremely low (below 4 ppmv @ 7% O₂), and well below the promulgated NSPS (50-150 ppmv @ 7% O₂). Figure 3 depicts the calculated main effects and control limits for the CO responses. Based upon this data, the excess air and primary/secondary/tertiary air split factors had the two largest effects, respectively. However, only excess air can be considered a significant factor since it was outside of the control limits. In order to determine if the other factors were significant, the common cause variation (materials, methods, machines, measurement, or people) of the combustion tests would have to be reduced, so that tighter control limits could be calculated, or the high and low levels of the insignificant factors would have to be expanded to produce a larger main effect.

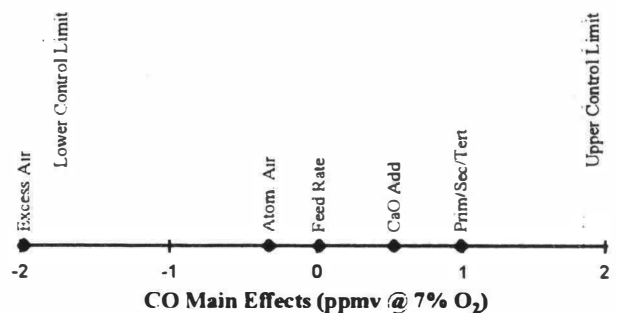


FIGURE 3 - PLOT OF MAIN EFFECT AND CONTROL LIMITS FOR CO.

As expected, CO emissions are inversely proportional to the amount of excess air. If these data are extrapolated based upon an assumed exponential curve, excess air levels approaching 10% may be feasible, with CO emissions still well below the promulgated NSPS. However, this prediction should be verified through actual combustion data.

Sulfur Dioxide (SO₂)

SO₂ emissions ranged between 42 and 57 ppmv @ 7% O₂ for all eight combustion runs, without any acid gas scrubbing. These emissions are slightly higher than the promulgated NSPS (30 ppmv @ 7% O₂). Figure 4 depicts the calculated main effects and control limits for the SO₂ responses. Based upon this data, the CaO addition and primary/secondary/tertiary air split factors were the largest main effects, respectively. However, all main effects were inside the control limits and can be considered insignificant factors for these combustion tests.

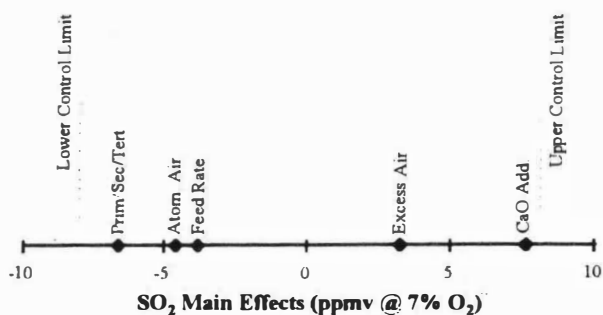


FIGURE 4 - PLOT OF MAIN EFFECT AND CONTROL LIMITS FOR SO₂.

The control limits for the SO₂ response were much broader than the previous control limits for CO. A possible explanation why no statistically significant main effects were determined from the SO₂ response could be a high level of measurement variation or sulfur variation in the slurry fuel. Based upon averages only, SO₂ emissions were 7.6 ppmv lower for the slurry fuel without CaO, which is counter to the reason for adding CaO. However, this difference was not statistically significant.

Nitrogen Oxides (NO_x)

NO_x emissions ranged between 125 and 224 ppmv @ 7% O₂ for all eight combustion runs, without catalytic or noncatalytic reduction. These emissions ranged from well below to well above the promulgated NSPS (150 ppmv @ 7% O₂). Figure 5 depicts the calculated main effects and control limits for the NO_x responses. Based upon this data, the CaO addition, slurry feed rate, and excess air factors had the largest effects, respectively. All three of these main effects were outside the control limits and can be considered significant factors.

This data reconfirms existing literature that higher excess air levels produce higher NO_x emissions (at a similar combustion temperature). As for the slurry feed rate, it is proposed that the higher slurry feed rate produced statistically significant higher NO_x emissions due to higher flame and combustor temperatures.

If NO_x emissions from each combustion run are plotted against combustion temperatures, a linear regression produces an R² = 0.84, indicating that combustion temperature may be a dominant factor for NO_x emissions with the other statistically significant factor dependent upon combustion temperature. Combustion temperatures below 1960°F produced NO_x responses below the 150 ppmv promulgated NSPS.

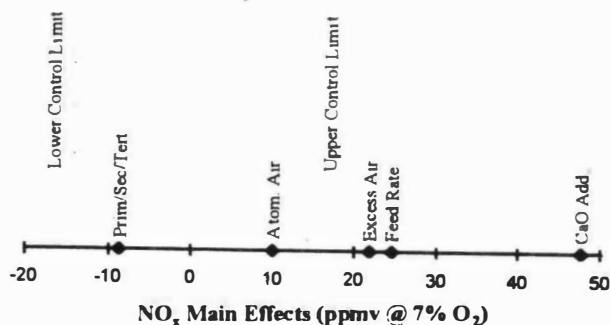


FIGURE 5 - PLOT OF MAIN EFFECT AND CONTROL LIMITS FOR NO_x.

Unexpectedly, the CaO addition factor produced the largest effect upon the NO_x emissions. At this point, the effect of CaO on NO_x emissions is not understood. More detailed statistical experiments are required with careful control of combustion temperatures to eliminate possible influence by temperature variations.

Ash Carbon Content

For all eight runs, the carbon content of the collected combustion ash was below 1.5 wt.% (moisture free basis), indicating an extremely good burnout of the carbonized RDF slurry fuel. Figure 6 depicts the calculated main effects for the carbon content of the collected combustion ash. Since only one ash sample was analyzed from each run period, control limits can not be calculated, and statistical significance of each main effect can not be determined. Based upon magnitude only, CaO addition and Atomizing Air had the largest main effects.

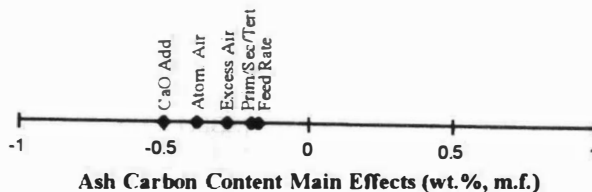


FIGURE 6 - PLOT OF MAIN EFFECTS FOR ASH CARBON CONTENT.

CONCLUSIONS

The carbonized RDF slurry fuel combusted exceptionally well, under conditions which were typical of a pc- or oil boiler

When compared to promulgated NSPS, emissions of CO and NO_x were as much as 99% and 21% lower than the proposed NSPS, respectively. SO₂ emissions were slightly higher than the proposed standards. However, when compared to coal (whose SO₂ emission regulations are much less stringent), the carbonized RDF slurry fuel would be considered a premium ultra-low sulfur fuel, even under Phase II of the Clean Air Act Amendments of 1990 (CAAA). Under the CAAA, up to 30% of the coal boiler's input could be the carbonized RDF slurry fuel, and SO₂ emissions would be regulated under the less stringent coal standards.

These combustion tests have clearly outlined typical boiler operating conditions and performance for the carbonized RDF slurry fuel, and will create a foundation for future combustion tests with the slurry fuel, which will characterize dioxin/furan and trace metal emissions under preselected constant boiler conditions.

FUTURE DEVELOPMENT

Additional carbonized RDF slurry fuel will be produced in a pilot plant run scheduled for January 1996. The objective of this pilot plant run will be to determine the effects of recycling filtrate water and feed stock RDF variations on slurry carbonization performance. The carbonized slurry fuel produced from these experiments will also be combusted in the pilot scale pc/oil boiler simulator in February 1996, and dioxins/furan and trace metal flue gas emissions will be determined by a certified stack sampling services firm. The combustion conditions to be used in these future tests will be based upon the results presented in this paper.

The overall objective of this pilot plant research is to accumulate the necessary engineering data to design a sizable demonstration facility (5 to 60 TPD feed RDF, dry basis). Design of the demonstration facility is tentatively scheduled to begin in mid-to-late-1996, dependent upon selection of a suitable host site and appropriate demonstration partners. SlurryCarb™ process development also continues with additional feed stocks including: plastic wastes, municipal and industrial sewage sludge, forest and pulp/paper industry wastes and byproducts, agricultural wastes and other cellulose materials.

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ABBREVIATIONS

- CAAA - Clean Air Act Amendments of 1990
- CaO - Calcium Oxide
- CO - Carbon Monoxide
- CTF - Combustion Test Facility (pc/oil boiler simulator)
- CWF - Coal-Water-Fuels
- CWM - Coal-Water-Mixtures
- DOE - U.S. Department of Energy
- EERC - Energy & Environmental Research Center
- EPA - U.S. Environmental Protection Agency
- HHV - Higher Heating Value
- m.f. - Moisture Free
- MRF - Material Recovery Facility
- MSW - Municipal Solid Waste
- MWC - Municipal Waste Combustion
- NO_x - Nitrogen Oxides
- NSF - U.S. National Science Foundation
- NSPS - New Source Performance Standards
- pc-boiler - pulverized coal boiler
- RDF - Refuse Derived Fuel
- SO₂ - Sulfur Dioxide
- wt.% - Weight Percentage