Appendix I

North Carolina State University's Pyrolysis Technology: Emissions of Particulate Matter and Nitrogen Oxides Using Poultry Litter as a Feedstock

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1. Summary

This report describes results from emissions testing conducted by the Virginia Cooperative Extension (VCE) and Farm Pilot Project Coordination (FPPC) to determine whether the North Carolina State University pyrolysis technology proposed for demonstration as a heat source for a radiant floor heating system for two poultry houses in Tyaskin, MD, will meet Maryland emissions requirements.

The system would treat 200 pounds of poultry litter per hour. Assuming a range of poultry litter Btu values between 3,500 and 6,500 Btu/lb, the proposed demonstration system would have a feed input Btu value ranging from 0.7 to 1.3 MBtu/hr. Hence, the system would be required to meet emissions requirements for particulate matter (PM) and nitrogen oxides (NOx) for systems under a 1.5 MBtu/hour threshold; these requirements are 0.35 lbs/MBtu of PM and 0.30 lbs/MBtu of NOx. Assuming a Btu value for the poultry litter in ranging from 3,500 to 6,500 Btu/lb, emissions from the pyrolysis unit would need to fall between 0.245 to 0.455 lbs/hr of PM and 0.21 to 0.39 lbs/hr of NOx in order to meet Maryland's permit thresholds.

Neither VCE nor FPPC provide certified emissions testing services. Hence, these results should be considered preliminary and supplemented with testing from certified emissions testing service providers. However, based on this preliminary data using U.S. EPA Method 5 for PM and a Testo 350 Multigas Portable Emissions Analyzer for NOx, it appears that the North Carolina State pyrolysis technology has the potential to meet Maryland biomass permitting requirements, potentially without emissions controls.

2. Pyrolysis Technology Description

The North Carolina State pyrolysis system captures energy and biochar using poultry litter as a feedstock. The technology (US patent 20090250331) is clean and efficient. In principle, the pyrolysis chamber is essentially a counterflow heat exchanger (Figure 1).

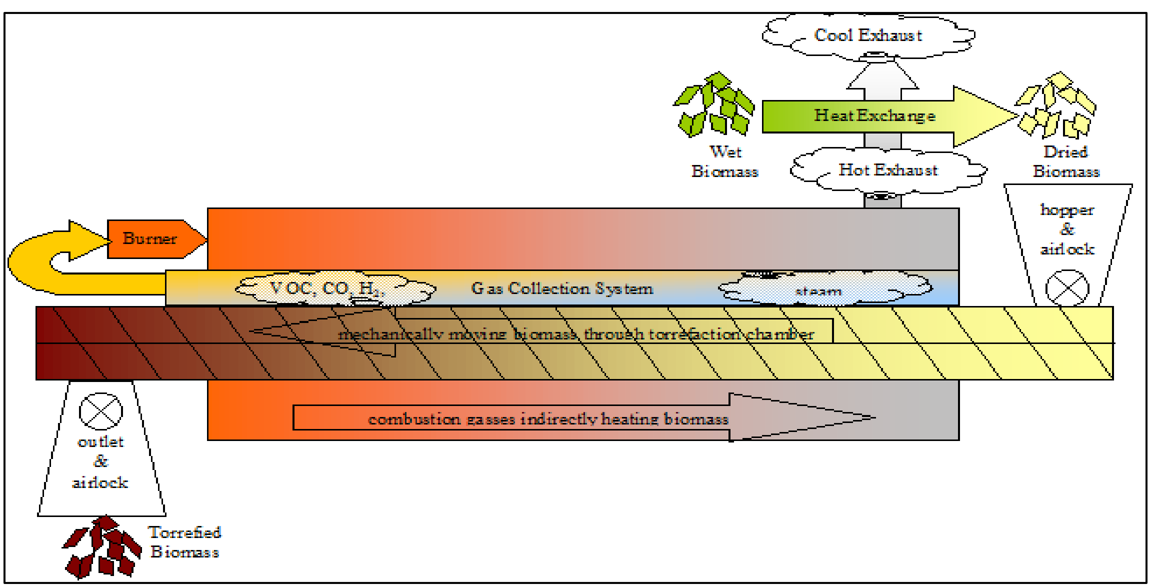

Figure 1. Conceptual schematic of the North Carolina State pyrolysis system

Combustion gases indirectly heat the raw poultry litter as it moves through the system. As the temperature of the poultry litter rises, the litter produces pyrolysis gases. The pyrolysis process occurs in the absence of oxygen, so the system is designed to minimize the introduction of oxygen to the pyrolysis chamber.

Unlike other pyrolysis systems, the synthesis gas produced through the pyrolysis process is not condensed to capture bio-oils; instead, the gases are fully combusted. This occurs by pulling the synthesis gases into a separate combustion chamber where air is added to induce combustion. The completely oxidized gases are then directed around the enclosed litter to provide the heat that drives the pyrolysis process. The air introduced to the secondary chamber is never in direct contact with the pyrolyzing biomass to facilitate a zero-oxygen environment in the pyrolysis chamber. Emissions exit the system where hot air can be captured for use as a source of heat.

3. Emissions Testing

The emission data for this study was collected at North Carolina State's Animal and Poultry Waste Management Center by John Ignosh of VCE and Preston Burnette of FPPC. Neither Ignosh nor Burnette are certified stack emissions testers. Hence, these results should be considered preliminary and confirmed with a certified stack-testing company.

3.1 Particulate Matter Emissions Methods

They pyrolysis system is rated for 600 lbs/hr for biomass, but due to the variable nature of poultry litter, the system can have runaway conditions in which the temperatures exceed the normal operating temperature and the poultry litter enters a gasification state rather than pyrolysis, producing more synthesis gas than the system needs. While adding more combustion air can control this, the adjustment must be made manually because the system is not currently automated. If the operator does not catch high temperature conditions in time, the system has to be shutdown to allow the system to cool before continuing operation.

Given the potential for the system to exceed the pyrolysis temperature range, the decision was made to run at two lower poultry litter feed rates (150 and 450 lbs/hr). This ensured very stable conditions for manual operation so that the emissions test would not be interrupted by a system shutdown. Since the system is rated for 600 lbs/hr of biomass, it has an input rating between 2 to 3.5 MBtu/hr. To maintain that rating for proper air flow through the entire system, propane was used as a secondary fuel. In normal operation, propane is used only during start-up and the flame temperature is kept between 1050° to 1250° C. The operator set the burner (which is automated) to maintain the flame temperature between those temperature set points.

Two runs were conducted on successive days. Data on PM and NOx emissions were collected from each run. The first run used 150 lb/hr of poultry litter and approximately 0.697 MBtu/hr (or 7.66 gallons) of propane. The poultry litter moisture value was 35% with a HHV of 6,500 Btu/lb. This provided a fuel input rate of approximately 0.6 MBtu/hr from the poultry litter. The flame temperature during this run was stable at 1050° C. The first test had a total sampling time of 120 minutes.

The second run used 450 lb/hour of poultry litter and approximately 0.275 MBtu/hr (or 3.02 gallons) of propane. Poultry litter contained 25% moisture with a HHV of 6,500 Btu/lb and provided approximately 2.0 MBtu/hr. The flame temperature during this run was stable at 1150° C. The second test had a total sampling time of 72 minutes.

- **EPA Method 1:** The stack diameter is 24 inches. Two 3-inch ports were installed 90 degrees from each other. The ports were 48 inches downstream of an elbow and 84 inches from the stack exit. Twenty-four points of traverse with 12 points at each port were used for sampling.
- **EPA Method 2:** A professional Method 5 sampling train from Apex Instruments with a standard calibrated "S" type pitot tube with a Cp value of 0.84 was used for EPA Method 2. Due to the low velocity of the stack gases (under 0.05 in H2O), a digital micro manometer for the differential pressure was deployed. This instrument is an ADM-850L Airdata multimeter from Shortridge Instruments. It was chosen based on the suggestion of Walter Smith, an expert in stack emissions sampling and one of the people who authored some of the EPA air emissions testing methods currently still in use today.
- **EPA Method 3A:** The Testo's O2 and CO2 sensors were not working properly so determination of the molecular weight using the Testo was not possible. Hence, previous data collected with the instrument from a poultry litter combustion technology manufactured by Wayne Combustion (the Global Re-Fuel system) was used to determine the molecular weight. In the previous test, the same Testo analyzer was used on a poultry litter fired combustion system where O2 and CO2 values were 10% each.
- **EPA Method 4:** The wet/dry bulb test to find the approximate moisture content of the stack gases.
- **EPA Method 5:** The Method 5 sampling train from Apex Instruments was used to take the PM samples. The average isokinetic values were calculated and found to be 103.6% for the first run and 96.2% for the second run. During each run, two sampling points out of 24 were not within 10% of isokinetic range. The dry gas meter and orifice are due for inspection and calibration. The sampling train passed the initial leak test, but failed the post leak test for both runs due to the ferrule on the nozzle softening too much due to the stack temperature.

NOx emissions were measured using a Testo 350 Multigas Portable Emissions Analyzer. The Testo 350 is a portable flue gas analyzer for professional flue gas analysis. The instrument consists of a control unit for displaying readings and a measuring instrument. The measuring instrument holds up to six different gas analyzers based on the application. A plug-type contact (i.e., databus cable) is used to connect the control unit to the measuring instrument. The Testo 350 is designed to provide real-time emissions control and inspection of compliance information about industrial furnace systems (i.e., processing plants, power plants). Gases at each site were measured in parts-per-million.

Emission rates were calculated by first converting the volume ratio to a concentration in mg/m3. The following equation was used to determine concentrations: where Y is the volume ratio, MW is the gas molecular weight, P is pressure, R is the Ideal Gas Constant, and T is the temperature within the stack. The rate in lbs/hr were calculated based on the actual flow rate through the stack.

The test port was pre-drilled approximately 18 inches above the Method 5 port locations. The Testo probe was not traversed in the stack during sampling. The probe was inserted into the stack approximately 5 minutes before the Method 5 test started, and it was terminated approximately 5 minutes before the Method 5 test ended.

The equation below was used to calculate the NOx emission rates for both runs, resulting in NOx values in mg/m^3.

$C = Y * MW * (P/RT) * 10^{-3}$
C = will yield mg/m^3
Y = ppm
MW = 46.01 g/mol
T = Kelvin
P = atm (absolute stack pressure, since stack pressures are usually just below or just above atmospheric, a value of 1 atm was used)
R = 8.205×10^{-5} or 0.00008205 m^3*atm/(K mol)

C* (flow rate/time) (in this case, lb/hour) yielded NOx emissions results in lb/hour.

NOx values were calculated based on the average value of NOx over the sampling time and the highest value during that time for both runs (150 and 450 pounds of poultry litter per hour).

3.2 Particulate Matter and NOx Emissions Testing Results

EPA Method 3A results: Using O_2 and CO_2 values of 10% each, measured using the Testo analyzer for emissions testing on the Global Re-Fuel unit fueled with poultry litter at the Wayne Combustion facility in Indiana, we calculated a Fo of 1.09, which is very similar to wood combustion values.

EPA Method 5 results: Average isokinetic values were found to be 103.6% for the first run (150 lbs/hr of poultry litter) and 96.2% for the second run (450 lbs/hr of poultry litter). During each run, two sampling points out of 24 were not within 10% of isokinetic range. This could reflect a need to inspect and calibrate the dry gas meter and orifice. The sampling train passed the initial leak test, but failed the post leak test for both runs due to the ferrule on the nozzle softening too much due to the stack temperature.

Results from emissions testing are summarized in Table 1. Results from EPA Methods 1-5 indicated that, at a poultry litter feed rate of 0.6 MBtu/hr and a propane feed rate of approximately 0.697 MBtu/hr, PM emissions from the North Carolina State pyrolysis unit were 0.140 lbs/hr. At a poultry litter feed rate of 2 MBtu/hr and propane feed rate of 0.275 MBtu/hr, PM emissions were measured at 0.286 lbs/hr.

Results from the Testo meter indicated that at the 0.6 MBtu/hr poultry litter and 0.697 MBtu/hr propane feed rate, NOx emissions based on the average measured NOx values over the course of the test were 0.0069 lb/hour. Using the highest measured NOx value during the test, emissions were 0.0125 lb/hour. At a poultry litter feed rate of 2 MBtu/hr and propane feed rate of 0.275 MBtu/hr, NOx emissions based on the average measured NOx values over the course of the test were 0.0023 lb/hr. Using the highest measured NOx value during the test, emissions were 0.0200 lb/hr.

Table 1. Measured propane and NOx emissions results from the North Carolina State pyrolysis unit fueled with a mixture of poultry litter and propane

Poultry litter feedrate (MBtu/hr)	Propane feedrate (MBtu/hr)	PM Emissions (lb/hr)	NOx lbs/hr using average values measured during the test period (lb/hour)	NOx emissions using highest value measured during the test period (lb/hour)
0.6	0.697	0.140	0.0069	0.0125
2	0.275	0.286	0.0023	0.0200

4. Discussion

Assuming a range of poultry litter Btu values between 3,500 and 6,500 Btu/lb, the proposed demonstration system would have a feed input Btu value ranging from 0.7 to 1.3 MBtu/hr. Hence, the system would be required to meet PM and NOx emissions requirements for systems under a 1.5 MBtu/hr threshold, which are 0.35 lbs/MBtu of PM and 0.30 lbs/MBtu of NOx. Assuming a Btu value for the poultry litter ranging from 3,500 to 6,500 Btu/lb, the emissions from the pyrolysis unit would need to fall between 0.245 to 0.455 lbs/hr of PM and 0.21 to 0.39 lbs/hr of NOx in order to meet Maryland's permitting thresholds.

Given that data was collected from a larger unit than is proposed in Maryland and that propane was used as a fuel along with poultry litter, the results from this test are not directly transferable to the smaller system that would be fueled (aside from start-up) completely by poultry litter.

However, emission factors from propane are well established by the EPA. In clean-burning systems, propane is a relatively low-emissions fuel with respect to filterable PM.

Specifically, the EPA emissions factor for propane used in commercial boilers for PM is 0.4 lb/1000 gal. For NOx, the emissions factor is 14 lbs/1000 gal.[1]

Based on these EPA emissions factors, anticipated emissions for the propane feed rate were 0.0031 lbs/hr of PM and 0.11 lbs/hr of NOx for the first run (using 0.6 MBtu/hr of poultry litter and 0.697 Btu/hr of propane). For the second run using 2 MBtu/hr of poultry litter and 0.275 MBtu/hr of propane, PM emissions from propane based on EPA emissions factors should have resulted in 0.0012 lbs/hr of PM and 0.04 lbs/hr of NOx.

Table 2 compares the predicted PM and NOx emissions factors based on EPA emissions factors with measured results. The anticipated PM emissions values based on the EPA emissions factors are very low and represent a small fraction of the measured PM (2.2% for the first run and 0.4% for the second run using the higher poultry litter feed rate). Therefore, it is likely that the majority of PM emissions are associated with the poultry litter biomass.

However, the NOx emissions predicted by the EPA emissions factors are considerably higher than measured. For the first run, the predicted NOx emissions rate from propane alone using EPA emissions factors is 8.8 times higher than NOx emissions reported for both propane and poultry litter using the highest measured value. For the second run, predicted NOx emissions from propane alone are twice the NOx value reported using the highest measured value for both propane and poultry litter.

Table 2. Predicted PM and NOx emissions based on propane emissions factors compared to measured propane and NOx emissions results from the North Carolina State pyrolysis unit fueled with a mixture of poultry litter and propane

Run*	Measured PM Emissions (lb/hr)	Predicted Propane PM Emissions (lb/hr) based on EPA emissions factor	Measured NOx lbs/hr using average values measured during the test period (lb/hour)	NOx emissions using highest value measured during the test period (lb/hour)	Predicted NOx emissions (lb/hr) based on EPA emissions factor
1	0.140	0.0031	0.0069	0.0125	0.11
2	0.286	0.0012	0.0023	0.0200	0.04

*Run 1: Poultry litter and propane feed rate of 0.6 and 0.697 MBtu/hour, respectively. Run 2: Poultry litter and propane feed rates of 2 and 0.275 MBtu/hour, respectively.

The difference in predicted NOx emissions associated with propane and measured NOx emissions from the system using both poultry litter and NOx could be associated with several unique components of this system. First, it is possible that this system is cleaner burning than typical commercial boilers. Second, it is also possible that ammonia released by the pyrolyzing poultry litter is reducing NOx emissions in the combustion chamber. The

[1] Emission Factor Documentation for AP-42 Section 1.5 Liquefied Petroleum Gas Combustion. By Acurex Environmental Corp, Edward Aul & Associations, and E.H. Pechan and Assoc. Available at: http://www.epa.gov/ttnchie1/ap42/ch01/bgdocs/b01s05.pdf.

EPA has indicated that this may be the case in low NOx firing systems, in which ammonia in the air would react with NOx to form nitrogen gas and water, thereby reducing NOx emissions.

Therefore, based on EPA emissions factors, it appears that propane is contributing minimally to PM emissions and significantly to NOx emissions; however, when introduced into the pyrolysis technology in the presence of poultry litter, NOx emissions are significantly lower than expected.

For purposes of evaluating the potential for a similar pyrolysis system (based on the larger North Carolina State design but using a smaller feed rate as proposed for demonstration in Maryland), PM and NOx emissions data based on these results were extrapolated to estimate emissions from a smaller system fueled completely by poultry litter. This approach should be viewed with caution and confirmed with certified emissions testing using poultry litter as the sole fuel source once a smaller unit is constructed.

With these caveats, extrapolation of the preliminary emissions testing data for the North Carolina State system suggests that the PM values would be approximately 0.187 lbs/hr and NOx values would be in the range of 0.016 lbs/hr for a similar unit with a poultry litter feed rate of approximately 200 lbs/hr. If these extrapolated values reflect emissions from the smaller system fueled solely by poultry litter, they would fall well within the range required for biomass permitting in Maryland. It is also important to consider that Maryland may have other permitting requirements and that the poultry litter used as a fuel will need to meet federal fuel legitimacy requirements.

Assuming these preliminary values are confirmed by a certified stack emissions testing company, it appears that the North Carolina State pyrolysis technology has the potential to meet Maryland biomass permitting requirements without the need for additional emissions controls.