Demonstration of a Small Modular Biopower System Using Poultry Litter

DOE SBIR Phase-II
Final Report

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Community Power Corporation

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1.0 Background

Introduction

On-farm conversion of poultry litter into energy is a unique market connected opportunity for commercialization of small modular bioenergy systems. The United States Department of Energy recognized the need in the poultry industry for alternative litter management as an opportunity for bioenergy. The DOE created a relevant topic in the December 2000 release of the small business innovative research (SBIR) grant solicitation. Community Power Corporation responded to this solicitation by proposing the development of a small modular gasification and gas cleanup system to produce separate value streams of clean producer gas and mineral rich solids. This phase II report describes our progress in the development of an on-farm litter to energy system.

The Industry Need:

On-farm heating needs for broiler chicken production farms are substantial, equating to nearly $24,000 each year for a typical 4-house farm (~$1/gal LPG). The income for a small poultry production enterprise is less than ~$70,000 above expenses. The net operating income after depreciation of buildings and equipment is just ~$30,000/yr.

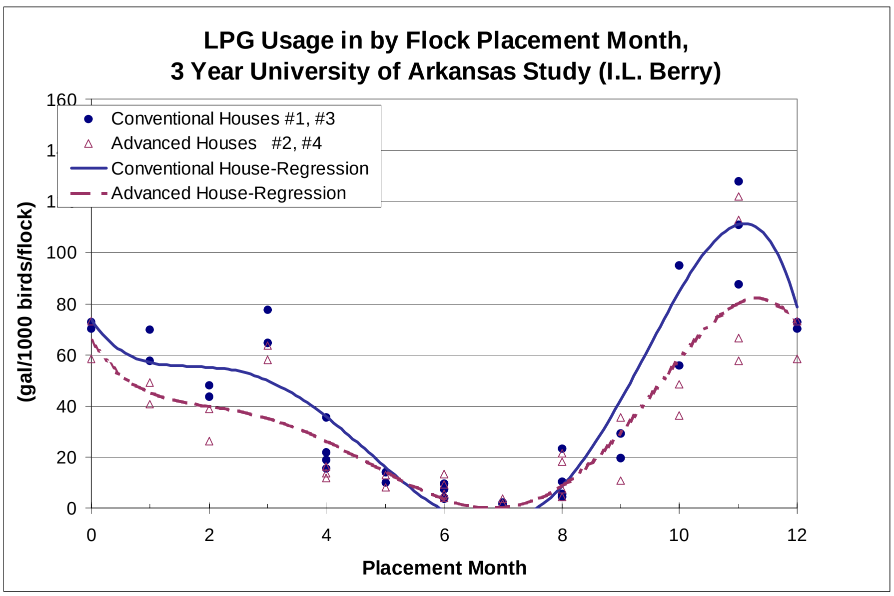
Figure 1 Poultry Litter Stockpiled in Storage Building-Arkansas

Heat is important for poultry production to optimize growth to market weight. Space heating is important during the placement of the brood (young chicks) because they cannot sustain their body temperature by metabolism alone. Brooding is the most heat energy intensive stage of production. Heating is also important in the winter time to achieve optimum production weight gain relative to feed consumption. The concern in the industry is that heating fuel costs can be volatile in some years and are expected to rise in the future. The price volatility of heating fuels can be a hardship on the poultry farmer and equates to an energy security concern in this sector. Rising fuel costs in the poultry industry will eventually be felt by the U.S. poultry meat consumer. Less important is the annual electricity expense, which is about $8,400 per farm and more stable (~ 7 cents/kWh).

Meanwhile, a typical broiler chicken production farm generates 440 dry tons of litter per year (~ 1 dT/1000 birds). The problem is that environmental concerns—water quality issues and eutrophication (premature aging and algae growth caused by mineralization) of local lakes and rivers—within the dense poultry production regions severely limit conventional land application of litter. Often no more than 50% of the litter can be land applied according to nutrient management programs and in some cases much less than that. The result is that abundant litter stockpiles have been generated with no practical or economic disposal option. Although land application is valued at ~$12.50/ton for the farmer in wholesale-displaced minerals, if allowed at all, the *bio-energy* value is nearly <u>$100/ton</u>. Moreover, the mineral components of poultry litter are recoverable in the litter ash and these may have additional wholesale value (~$12.5/T litter, or about $50/T ash).

Both heat and electrical energy are vital to the broiler production house, but heating fuel is the largest portion of utility costs. Heat is essential for the brooding period of a newly hatched chick, and heating in the winter helps optimize feed consumption and growth.   The peak heat demand is in the fall, winter and spring months (Figure 2), whereas electrical energy use peaks in the summer months (Figure 3).

Figure 2 LPG Usage per flock by placement month: peak demand is in the winter months [University of Arkansas Data] [1,2]. Annual fuel costs can reach $24,000/yr.



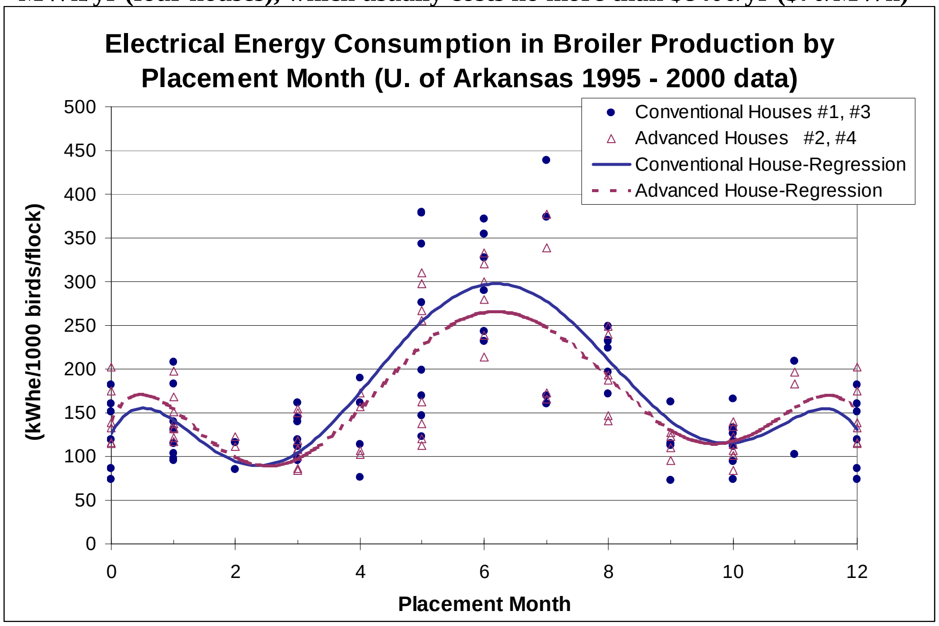
The poultry farm with four houses (small broilers) has a heating fuel demand of ~22,000 to 24,000 gallons. At $1/gal LPG, the annual heating fuel cost for a four house farm in a warm climate such as Arkansas is as much as $24,000/year.   If one compares the energy content of poultry litter to the energy content of liquefied propane, it is clear that a dry ton of poultry litter has a substantial amount of energy, approximately 99-gal LPG equivalent/dry T at 70% conversion efficiency. The total amount of annual litter product is sufficient to meet all of the heat energy needs for the entire broiler chicken farm.

$$\text{Annual Litter} = \left(\frac{440\ dry\ T}{farm}\right) x \left(\frac{120\ therm}{dT}\right)\left(\frac{70\%\ efficiency}{1}\right) x \left(\frac{1\ gal\ LPG}{0.845\ therm\ (LHV)}\right)$$
$$= 43{,}740\ gal\ LPG\ equiv$$

Electrical energy is important in all seasons for automatic feed delivery and especially for ventilation and cooling purposes in the summer when peak electrical consumption occurs.

Detailed discussion of heat and electrical energy needs of the broiler chicken production farm can be found in University of Arkansas literature[1,2] with additional information summarized in our phase I report.[3]

Figure 3 Electrical energy use for a boiler production farm is ~100 to 120 MWh/yr (four houses), which usually costs no more than $8400/yr ($70/MWh)



Poultry litter is a substantially difficult fuel to utilize. There is a lack of appropriate technology available for on-farm conversion. Only an on-farm application will return substantial revenue for the farmer. However, there is some hesitancy by farmers to change litter management practices. Even poultry integrators may be resistant to allow farmers to change litter management practices if there is a risk of harming the birds that the poultry companies own. Strong environmental pressure exists to develop alternative management practices that are safe for the environment. Legal requirements for appropriate litter management may also force the implementation of alternative strategies for litter management. To overcome one of the primary barriers to the adoption of alternative litter management practices, these new practices should return some economic benefit to the farmer.

On-farm thermochemical conversion of poultry litter, such as by gasification or combustion, is one of the remaining options that will benefit the farmer economically. Selling litter off the farm can yield as little as $3/ton after transportation cost, or less than the perceived value for land application ($12/T). Shipping litter to off-farm applications is a biosecurity concern for the farmer and his neighbors. It can even result in a net loss of income for the farmer because of high shipping and handling charges. In contrast, on-farm conversion offers the opportunity to extract

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[1] Berry, Ivan, L., "Use of Liquified Petroleum Gas in Four Broiler Houses." A report to the Foundation for Organic Resources Management (FORM); June 30, 1999.

[2] Tabler, G.T., and Berry, I.L., "Applied Broiler Research Unit Report: Ten-Year Summary of Broiler Production Results." Report by the Center of Excellence for Poultry Science and the Biologival and Agricultural Engineering Department, University of Arkansas. (2001)

[3] Reardon et. al., Phase I Report (2001). www.osti.gov/dublincore/gpo/servlets/purl/794292-6l279H/native/

the more valuable energy content of poultry litter to displace significant energy costs "on the farm" while sterilizing and concentrating mineral by-products (phosphate and potash) that have secondary economic value. Minerals recovered from litter ash could potentially be sold or used as fertilizer additives by larger enterprises.

Gasification is preferable to combustion for the on-farm application because toxic air emissions can be controlled more readily before final combustion. Also gasification offers the benefit of a more substantial scale with a single unit supplying fuel gas for the entire farm.

This DOE SBIR Phase II for development and demonstration will help bring forth new small modular gasification technology to help farmer's utilize poultry litter wastes on-the-farm. This novel approach addresses a pressing environmental concern for the ultimate disposition of poultry litter residues and helps displace expensive heating fuels. The on-farm solution avoids the cost, inconvenience and bio-security concerns of litter shipping and handling.

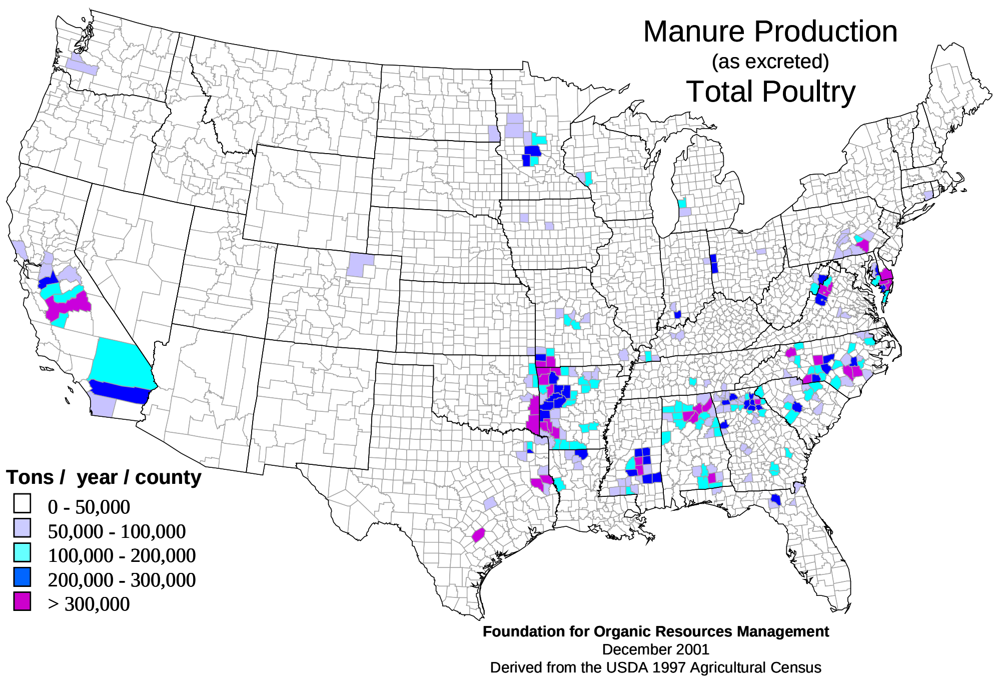


Figure 4 Regions of Concentrated Poultry Production, Manure Production Rates [FORM]

The Importance of the Poultry Industry to the U.S. Domestic Economy

The poultry industry's contribution to the US economy is worth nearly $22 Billion in gross domestic product.[4] The poultry industry's economic importance to the United States is significant, especially to the economies of many southern and mid-western states, but recent years have seen a leveling and even a decline in the industry's GDP. The poultry industry contributes 22 to 23% of the U.S. livestock GDP in recent years.

[4] Economic Research Service/USDA (2001)

The US presently dominates the world poultry export trade with its share accounting for 43% of the total world poultry exports in 1998. Broiler meat exports account for 17% of total domestic broiler production.[5] Volatility in world export prices can have a notable influence on the value of broiler production in the United States. The cost of environmental compliance is one factor that can influence the US export competitiveness. The utilization of poultry litter's bioenergy potential can support higher revenues for the poultry industry and help the poultry industry improve environmental and economic performance.

The continental United States map in Figure 4 illustrates regions of concentrated poultry production. These areas of dense poultry and manure production are regions of opportunity for bioenergy.

The top 20 broiler production states produce over 98 percent of the U.S. total. The top 5 broiler chicken production states in order are ***Georgia, Arkansas, Alabama, Mississippi, and North Carolina***. The top 5 turkey production states are ***Minnesota, North Carolina, Arkansas, Virginia, and Missouri***. Egg producing farms are not the target market for modular gasification systems since the manure is less well suited for gasification and may be more appropriately processed with wet anaerobic digestion.[6]

What is Poultry Litter?

A detailed assessment of poultry litter and the poultry industry is available in our phase I report, but some details are repeated here for completeness.[7]

Figure 5 Colorado Turkey Litter

Poultry litter is a by-product of concentrated poultry production and includes raw manure plus bedding (usually wood shavings, rice hulls or mixtures thereof) that has also absorbed the avian urine and also includes some spilled grains and salts that were fed to the birds. Litter on the house floor is usually around 25% moisture because the farmer controls the humidity inside the house. Litter generally has the consistency of sawdust, but with a higher bulk density (32 lb/ft^3 or 0.51 kg/L compared to sawdust ~10 lb/ft^3 or 0.16 kg/L). On the other hand, water is often spilled or leaked on to the litter so that it will form higher moisture agglomerates called "cake". Litter will variably contain feathers, bugs (dung beatles), mortality parts and other tramp materials (small rocks, dirt, nuts, bolts and wire). After cake removal, most litter will retain a broad particle size distribution from 0.015 to 0.5 inches and can generally be fed or transported with an auger and trough. Cake may require grinding or crushing before being used in a gasifier, but the bulk of the litter is suitable without any further processing.

[5] The United States Department of Agriculture (1990-2000), various publications.
[6] Jack Avens (Colorado State University) and Afroim Mazin, personal communications; Dec 2001.
[7] www.osti.gov/dublincore/gpo/servlets/purl/794292-6l279H/native/

Our interest is mainly in broiler litter, or the bedding product of broiler chicken and turkey production. There were approximately 8.8 billion head of broiler chickens produced in 2003. These birds excreted approximately 35 million tons of wet manure (8 lbs/bird excreted at 75% moisture). Of the 280 million head of turkey produced in 2003, these excreted 4.8 million tons of wet manure. Broiler chicken and turkey production is targeted because the litter is collected and handled dry (<25% moisture) and represents 95% of all poultry manure—approximately <u>10 million dry tons</u> of litter were produced by broiler chickens and turkeys in 2003.

CPC analyzed many litter samples from houses in the NW region of Arkansas. Results of chemical analysis for nutrient content are summarized below.

Table 1 Representative Nitrogen, Phosphorous and Potassium Values for AR Broiler Litter[8]

	% H_2O (wet basis)	Total N (lb/ton)	P_2O_5 (lb/ton)	K_2O (lb/ton)	Ca (lb/ton)
Minimum	2	22	18	23	18
Maximum	47	98	96	80	108
Mean	23	60	58	52	45

According to the University of North Carolina[9], the typical or average poultry house litter contains N-P-K ratios (lbs/ton) of about 72-68-47 for Broiler chickens, with ~20% average moisture; whereas, grower turkey litter is 56-63-40 (lbs N-P-K per ton). Applying poultry litter residues to crop soil will increase organic matter benefiting the soil's water-holding capacity and improve soil tilth. A soil analysis is important to determine the appropriate balance of N-P-K and Ca for the desired crop, and although poultry litter contains many of the valuable nutrients found in expensive commercial fertilizers, the N-P-K ratios may not be ideally suited to the soil nutrient needs and may require augmentation to yield optimum ratios.

Table 2 Poultry Litter Production Rates, Summary of UNC Data.[5]

Manure Source	Assumed House Capacity	Manure+Litter Accumulation (tons/house/yr)	Dry Solids content (% w.b.)	Dry Litter Accumulation (tons/house/yr)	Birds/House Annual	Dry Litter Accumulated Per Bird (tons/1000)
Broiler Chicken	20,000	126	78.6	99.0	110,000	0.9
Broiler Roaster	20,000	200	76.2	152.4	110,000	1.38
Turkey Grower Hen	10,000	200	73.2	146.4	175,000	4.18
Grower Tom	10,000	410	73.2	300.1	175,000	8.57

[8] Samples taken from poultry houses in the Northwest Arkansas region including pelletized litter, and litter with pine shavings and rice hulls mixed with pine shavings.
[9] Soil Facts: Poultry Manure as a Fertilizer Source. http://www.soil.ncsu.edu/publications/Soilfacts/AG-439-05

The Typical Poultry Farm

Figure 6 Typical 4-house Broiler Chicken Production Farm

The typical broiler chicken production farm has 4 houses, usually 40 ft wide by 400 ft long, and produces 110,000 birds per year per house, or a total of 440,000 birds per year per farm. There are larger broiler chicken production farms, perhaps with 8 or more houses, but most are small contract growers. Broiler chicken production is more vertically integrated than other livestock industries, meaning there are more contract grower farms that do not own the birds. Approximately 85% of all broiler chicken production farms are contract growers.

The broiler chicken farmer grows an average of 5.5 flocks per year in six week cycles. Many houses are designed for 20,000 bird flocks, but some houses are designed to hold 25,000 bird flocks. Our basic rule of thumb for dry litter production on the broiler chicken farm is 1 dry ton litter per 1000 birds. This value equates to the actual dry manure production rate of broiler chickens, reported to be 8 lbs/bird at 25% dry matter[10].

Broiler chicken production is an equipment intensive enterprise, but it has been shown to be profitable and provide income for many families in farm based economies. The typical broiler chicken farm may have income and expenses similar to those presented in Table 3 (average performance for farms participating in the Alabama Cooperative Extension System).

Table 3 Typical Poultry Farm Budget Based on Alabama Broiler Chicken Farms[11]

POULTRY FARM ANALYSIS REPORT		**Average Farm**	
For Year Ending December 31, 2003		Total ($)	¢ per lb.
INCOME		**172,439**	**5.07**
TOTAL OPERATING EXPENSE		**(103,446)**	**(3.04)**
INCOME ABOVE OPERATING EXPENSE		**68,993**	**2.03**
	Machinery Depreciation	(16,951)	(0.50)
	Building Depreciation	(21,744)	(0.64)
TOTAL (TAXABLE) OPERATING INCOME		**30,298**	**0.89**

Five operating expenses account for ~82% of operating costs for the poultry enterprise detailed below (Table 4). Utility costs contribute the highest portion of these expenses. LPG usage varies by season and geography, but a rough estimate of the heating cost is $24,000/farm. This equates to 24,000 gallons/farm at a price of $1/gal LPG.

It is already recognized that high fuel costs can cut into potential profits for poultry growers. Today's LPG price for poultry growers is ~$0.92/gal (Summer 2004), based on the Mont Belvieu

[10] Foundation for Organic Resources Management (FORM).
[11] Poultry Report Card 2003; (Poultry Enterprise Basis), Alabama Cooperative Extension System. www.aces.edu

spot price + $0.25/gal.[12] LPG prices may be even higher this winter.[13] It is impossible to predict the future price of propane, but based on trends over the past decade, the long-term average price could rise by $0.20 to $0.40/gal in the next decade. Market volatility, also a concern for the farmer, has the propensity to double the LPG spot price in difficult years.

Electricity usage and costs are more uniform at about 100 to 120 MWh/farm at $70/MWh (usually not more than $8400/farm).

Table 4 Operating Expense Details (Top Five Expenses)

Top Operating Expenses	Costs ($)	¢ per lb.
Utilities (LPG, power, water, tel)	33,339	0.98
Interest Paid	18,356	0.54
Labor Paid	14,540	0.43
Livestock Supply	9,922	0.29
Machinery Repairs	8,180	0.24
81.5% of all expenses:	84,336	2.48

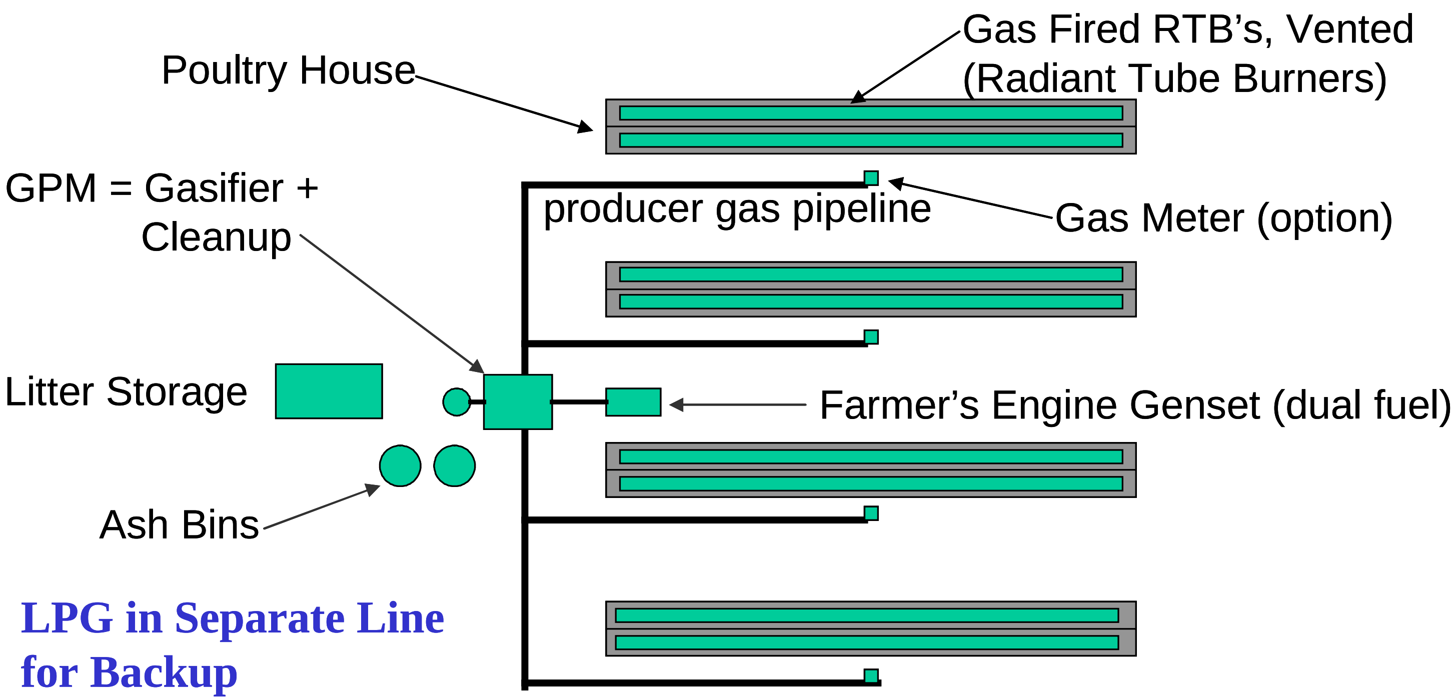
Turkey producing farms are often much larger and as many as 44% have corporate ownership. Approximately 56% of all turkey production farms are contract growers. Because turkey farms are larger and have more corporate ownership, this may be the best market entry point for the modular bioenergy system. Our rule of thumb for turkey litter production is 4.25 dry Tons litter per 1000 birds. No energy cost data was available for turkey production farms, however.

The Opportunity for Modular BioEnergy-Introducing the On-Farm System Concept

The basic concept for on-farm bioenergy is that fuel gas generated from poultry litter residues would be used to displace expensive heating fuels on the farm. A portion of the generated fuel gas could be used in the farmer's own backup generator to displace electricity if desired, but because electricity has a lower value than heat (considering overall conversion efficiency) and a smaller potential impact it should be a secondary application to heat. Concentrated litter ash product would be collected and might be sold off-farm for additional revenue. Minerals in the post gasification ash are much more concentrated than in litter and the ash is sterilized by the thermal oxidation process.

The proposed litter management system moves litter from a storage shed into the biomass gasification system. Gasification produces a vapor phase fuel at high temperatures that is subsequently cleaned to remove particulate matter and tars. After gas cleaning, it is cooled before distribution to the farm at large. [See Fig. 7] A single system would service the entire farms heat needs. This on-farm system could be purchased by the farmer, or could be owned and operated remotely by a larger litter management company (LIMCO) who sells fuel gas to the farmer through supply contracts.

[12] http://www.waterbornelpg.com/dailyprice.asp
[13] LPG price explained: http://www.aces.edu/department/poultryventilation/PEEMN-29PropanePriceMgmt.pdf

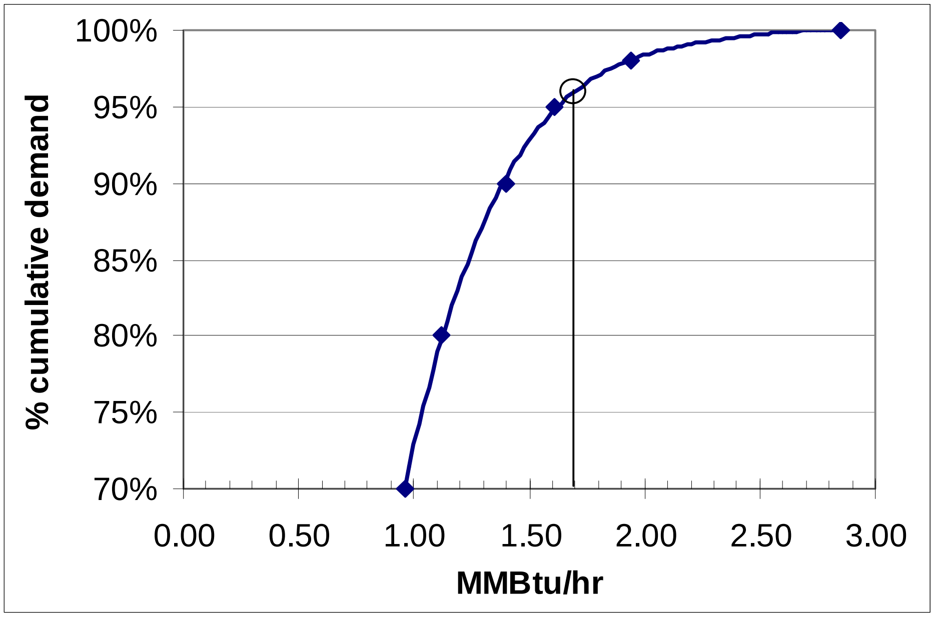


LPG in Separate Line for Backup

Low energy fuel gas, called "producer gas", generated by air blown gasification is suitable for firing in radiant tube heaters with simple modification of the gas orifice. This simple orifice modification has been demonstrated to be effective at CPC. These radiant tube burners (RTBs) have simple thermostatic control (fuel on/off) and can be used for poultry house brooding (with adjustable height positioning) and for wider poultry house heating (with near roof position). These RTBs are common to a variety of industries and are becoming known to the poultry industry with reports of increased energy efficiency, reduced ventilation requirements and improved heat distribution compared to "pancake" brooders.[14,15]

These radiant tube burners are an ideal method for burning "producer gas" to deliver heat to the poultry house because any incomplete combustion products can be vented out of the building without harming birds. This approach also gives a measure of safety in case the gasification system undergoes an upset condition. Gas supply to the RTBs is controlled by internal solenoid valves that are operated automatically with a thermostat.

Figure 8 Statistical Sizing Criteria for On-Farm Litter Gasification System. Target Scale is 1.7 MMBtu/hr, or ~95% of Cumulative Heat Demand



We propose that an on-farm litter gasification system be designed for a maximum litter gasification rate of 400 lb/hr. This system size would generate fuel gas at heat rates equal to 1.7 MMBtu/hr at 70% (LHV) gasification efficiency (1.6 MMBtu/hr at 65% efficiency). This scale is sufficient to meet 96% of the heat energy needs of the poultry farm. [see Fig. 8.]

The scale of the poultry litter gasifier need not meet the exact peak heat demand for the house, because it is more cost effective to meet 90 to 95% of the heat needs and add LPG for peaking.

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14 "Radiant Tuber Brooders for Poultry Houses" Report from the Field by Jim Donald and Mike Czarick; Auburn University Extension Service: http://www.aces.edu/department/poultryventilation/RadiantTubeHeatPaper.pdf

15 Cumberland Poultry Systems: http://www.cumberlandpoultry.com/english/radtube.html

Existing LPG connections in the house would be kept for backup and peaking. Statistical data collected over several years at the University of Arkansas [Table 5] was used to develop a basis for sizing gasification equipment for the typical 4-house poultry farm application. It is not economic to meet more than 95% of heating fuel demand because of diminishing fuel displacement opportunity relative to increased costs for capacity (diminishing returns).

Table 5. Statistical Sizing Criteria for Poultry House Furnaces[16]
(Equivalent LPG Consumption Rate gal/hr)

Cumulative Energy %	70%	80%	90%	95%	98%	100%
Conventional House #1	3.19	3.64	4.47	5.18	6.20	9.8
Conventional House #3	2.81	3.28	4.02	4.55	5.55	8.0
Advanced House #2	2.66	3.15	3.92	4.59	5.49	8.0
Advanced House #4	2.70	3.21	4.11	4.74	5.69	7.9
4-house average (sum) (gph)	**11.36**	**13.28**	**16.52**	**19.06**	**22.93**	**33.70**
Farm Scale System Peak Heat Rate (MMBtu/hr)	0.96	1.12	1.40	1.61	1.94	2.85
Peak Litter Gasification Rate (lb/hr at 70% eff)	229	267	332	383	461	678

Power generation as a primary product is not ideally suited for the poultry farm because the waste heat utilization opportunity is small. First, power use is mainly in the summer. Second, because power use is smaller in the winter, a much smaller amount of total heating bill would be displaced with waste heat recovery.

On the other hand, a novel concept for heat supply management is to use the farmer's own engine-generator equipment as ballast for the gas production module. On-site backup diesel generators are assumed to be standard equipment for most new grower contracts, and this hardware needs to be exercised regularly. These engine generators can be modified to run on dual fuel (10% diesel contribution) without spark ignition. There are also new technologies that do not require producer gas fueled diesel engines to be modified for spark ignition, yet enable them to operate at high compression ratios using very small amounts (<1%) of diesel pilot fuel in high turn-down injectors to achieve high pressure compression ignition[17]. This ballasting concept would work best if the farmer could negotiate a net metering contract with his local electric utility. (Net metering opportunities for poultry farmers may require legislative support). For example, the gas supply equipment would operate at maximum for heat delivery during the placement of the brood then gradually divert heat supply to electricity production to balance heat demand. Gasification capacity could be moderated as required with intelligent control systems to provide overall system balance and a waste gas flare can also be included for startup and idle.

There are over 86,000 poultry houses in the United States owned by tens of thousands of farmers. On-farm litter gasification has the potential to benefit thousands of poultry farmers in the United States. Whereas, farmers currently pay nearly $1.18/therm for heating fuel (~$1/gal LPG)[18], the

[16] Statistical sizing criteria derived from results of 3-year broiler production study, IBID. Berry (1999).
[17] Work performed at Colorado State University on non-spark natural gas engines with high pressure diesel fuel rails.
[18] Most poultry farms do not have natural gas service. LPG is purchased in large quantities by the poultry integrator and sold to the farmer at a low price to help the farmer. Even so, we note that farmer's fuel costs have risen by over

10 million tons[19] of litter generated by broiler chickens and turkeys each year is equal to about 1 billion gallons of LPG in fuel equivalents (142 gal LPG equiv/dry ton x 70% efficiency) when gasified. If ~52% of the annual litter product is used to displace 95% of all heating fuel used in the industry, then the potential fuel savings for the poultry industry is greater than $0.5 billion per year!

Techno-Economic Challenges

The techno-economic development challenge is to produce a reliable and automated system that is also affordable for the on-farm user. The on-farm user is presumably the poultry farmer but it could also be a larger litter management company (LIMCO) who may own and remotely operate fleets of equipment and sell produced fuel gas to farmers at contract prices competitive with commercial LPG.

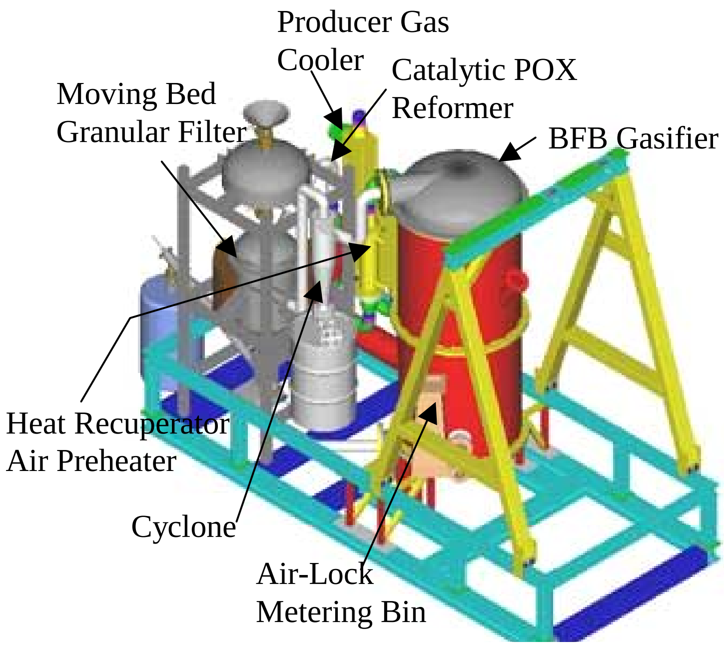

Figure 8 Solid Model of Phase II Pilot-Scale Litter Gasification System: 12" ID reaction zone, ~120 dry lb/hr; >500,000 Btu/hr GPR. A farm-scale system would be about 3-times capacity.

A farm-scale system would peak at 1.7 MMBtu/hr (500 kWth) or ~400 lbs/hour and should probably retail for less than $187,500 in production, or about $150,000 wholesale. Special financing or capital buy down may be afforded with the 2002 US Farm Bill, title IX, section 9006 to help reduce the farmer's capital burden to wholesale cost. If fuel prices rise over the next 15 to 20 years (assumed equipment life), the farmer would realize even better rates of return. A litter management company would need to operate many systems with a single operator and would need to include other added value products such as ash recycling and fertilizer sales.

Our technical challenge involves reliably producing high quality fuel gas without fouling burners or failure of the biomass gasifier. For example: no clinker production or loss of fluidization should occur within a reasonable maintenance cycle (6 to 8 wks). Clean, high quality fuel gas should be available at all times after a reasonable startup period. These goals are achievable, but should be appreciated as significant technical challenges when considering that the target fuel is high ash poultry litter (~25% ash on dry basis) with substantial amounts of volatile potassium present in the litter ash (>20% of the ash). The presence of any silica in the litter (for example from rice hull bedding) may also impact the gasifier reliability, because potassium silicate that can form inside the gasifier is a low melting point glass.

15% per year for the past three years. Prices as high as $1.35/gal were not uncommon last winter. LPG lower heating value (LHV) = 84,500 Btu/gal (API) = 0.845 therm/gal.

[19] Based on the USDA, Poultry Production and Value, Final Estimates 2002, April 2004. 1 dT Litter/1000 broiler chickens, and 4.2 dT/1000 broiler turkeys. Production statistics on the web: http://usda.mannlib.cornell.edu/reports

Secondly, the gas cleanup system should not create any new environmental problems such as tar-contaminated wastewaters. Wet-scrubbers are excluded from consideration in the cleanup system replaced by more advanced “dry gas cleanup” technologies. Clean gas approaches for biomass gasification include staged gasification with partial oxidation and/or hot gas filtration followed by catalytic reforming. If a low tar gas can be produced without using a wet scrubber, defined as 50 to 100 ppm tars, then cold filtration is possible above the water due point (40 °C). With a highly successful gas cleanup system (<25 ppm tar), then even ammonia recovery is possible plus fertilizer minerals that are recovered in the dry filter cake.

The unique challenge of poultry litter gasification is that the target biomass fuel is a compound commingled with substantial fertilizer constituents including roughly 3 to 4% each of ammonia, phosphate and potash. These essential nutrients for plant growth are an order of magnitude more concentrated in confined animal litter than they are in any other biomass feedstock. Moreover, ammonia presents a unique air emission concern for litter combustors and/or producer gas combustors. Post combustion “chemical NOx” (contrast to this to thermal NOx) emissions will be very high because theoretically 3% of the generated gas is ammonia. Therefore, appropriate technology is needed in the bioenergy system to reduce ammonia in the generated gas stream or to control NO_x emissions in combustors. Options for ammonia control include catalytically reducing ammonia to nitrogen and water before cooling the producer gas or to cool and separate the ammonia by condensation or membrane drying once tars and particulates are eliminated from the generated gas.

Figure 9 Manure spreader and tractor with an ammonia tank

The fertilizer constitution of litter (4% ammonia plus 25% mineral ash compared to wood with <1% mineral ash) is why it is presently and historically valued as a soil amendment. These constituents present operational reliability and gas cleaning challenges; however, if these fertilizer components can be separated from the biofuel at the farm-scale using bioenergy equipment, then transportation of the mineral fertilizer constituents becomes practical. The potential to recover ammonia is also attractive. The farmer’s interest in on-farm bioenergy may also be heightened when the traditional value of the litter can be retained, even though this has only secondary economic impact.

Conventional Litter Management: Land Application

On the average N/P ratios are 1.03 for poultry litter in Arkansas, and N/K ratios are 1.15. Since the nutrient needs for many forage grasses require N/P ratios that are 2.4 to 3.9, (for example rye grass, fescue, Sudan grass, wheat, Bermuda grass, and Bahia grass) the application of poultry litter on a nitrogen basis would lead to excess mineral levels in the soil. Excess application or the misapplication of litter residues to soil can result in excess phosphorous buildup, for example, that can be a concern for surface and groundwater through leaching and water runoff from rain. After seasonal plant growth much less nitrogen is retained in the soil compared to phosphorous, therefore, litter applications in subsequent years should be reduced with increased addition of nitrogen rich fertilizers as needed to improve crop production. Long-term over-application of litter could result in soil overloaded with various micronutrients leading to soil toxicity.

One of the more serious concerns for poultry litter utilization by land application, combustion or gasification is the presence of both organic and inorganic forms of arsenic (As) in poultry litter. Approximately 70% of chickens raised for meat receive doses of roxarsone, an organic form of arsenic. "Inorganic arsenic is a carcinogen, but organic forms—containing carbon and arsenic—are less toxic and used to combat avian disease and accelerate growth. Therefore, organic arsenic is an approved ingredient in roxarsone, a feed additive used in poultry and swine." [20] Most of the arsenic is excreted and would therefore be added to the litter. Some As is retained in tissues, particularly in the liver, in both inorganic and organic forms. Because the inorganic forms are also found in poultry tissues, it is reasonable to assume that inorganic arsenic will also be present in raw poultry litter.

Thermal oxidation (combustion or gasification) of the litter would likely transform all organic arsenic into its more toxic inorganic form. This means that any litter burning furnace or gasifier must have controls to minimize inhalation hazards of particulate matter (ash) and smoke (aerosols). Producer gas filtration will control such air emissions. Gasification or combustion furnaces will concentrate inorganic arsenic in the ash product. The presence of arsenic in litter is low, but how minor amounts of this contaminant may affect the salable value of the ash product is uncertain. The farm-cooperative that desires to recycle litter ash into higher value fertilizers will need to meet regulatory maximums for As.

Comparison of Litter's Value: Fertilizer, Heating Fuel or On-Site Electricity

Poultry litter has more raw value as a *biofuel* than as a soil amendment. Dedicated on-site power generation is not favorable because the retail cost of electricity is low in most poultry producing states (~$70/MWh), and the farmer's annual electric utility bill is relatively low compared to heating fuel costs. The value of litter to make producer gas for displacing propane is the best application. If the farmer has an existing generator, then using this for gasifier capacity ballast makes sense to increase the overall rate of return on equipment.

The value of litter as a fertilizer has been developed elsewhere. Most extension university fact sheets report $12 to $15/T litter for the economic value of land application. This normally includes the wholesale mineral value and nitrogen value of the litter. In our analyses the wholesale value of fertilizer minerals alone from litter ash is close to $12.50/dT litter (or ~$50/T ash, given litter with 25% ash, dry basis). An example calculation is provided below: A dry sample of poultry litter has 25% ash, which is comprised of 20% calcium oxide, 20% phosphate and 12% potash. Wholesale value of minerals is estimated to be about 50% of the retail value on a per ton basis as presented below:

Litter fertilizer value (based on wholesale minerals only) =

$$[0.2(\$10/T\ CaO) + 0.2(\$175/T\ \ phosphate) + 0.12(\$110/T\ \ potash)] * 25\%\, ash = \$12.55/\, dry\ Ton$$

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[20] "Chicken Little", Science News: This Week, Oct 25, 2003; Vol 164, pp. 259, 260. www.sciencenews.org

The value of litter as a *biofuel* is calculated based on its lower heating value (LHV). The LHV of dry litter is approximately 6000 Btu/dry lb (12-MMbtu/dry T, or 120-therms/dT, or ~14 MJ/kg), which equates to 4500 Btu/lb on an as received basis with 25% moisture. Litter has only about 70% of the energy of wood on a dry mass basis. However, if comparing with sawdust on a volume basis, poultry litter has 1.85 times (almost twice) the energy density of sawdust.[21] Feed rates for litter in a sawdust gasifier will therefore be about 46% lower.

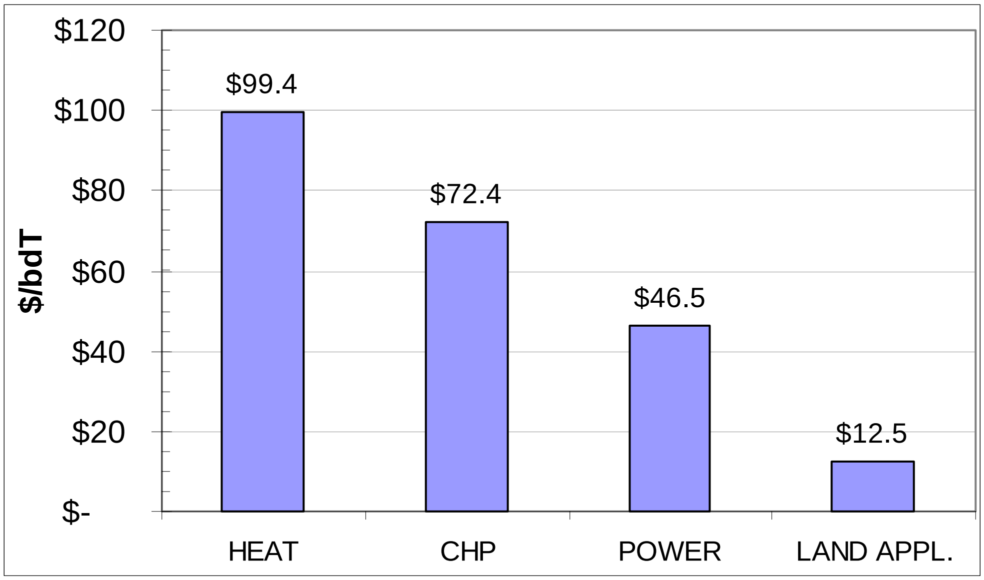


Figure 10 Comparison of the On-Farm Unit Value of Litter by Application

Assumptions

Heat: 70% gasification efficiency, $1/gal LPG ($1.18/therm), 120 therm/dry ton litter.
Power: 18.9% overall efficiency (70% gasification x 27% engine-generator), $0.07/kWh
CHP: 50% of waste heat is recovered and utilized (However, the farm is not ideal for CHP).

Table 6 Total Gross Energy or Fertilizer Savings for On-Farm Applications and Litter Usage

440 Total Litter (dry T/yr)

On-Farm Options	Unit Value ($/T)	Litter Use (T/yr)	Total Value ($/yr)
95% HEAT + 50% *POWER (not CHP!)	$ 84.5	**320**	$ 27,000
95% of HEAT (70% eff)	$ 99.4	**229**	$ 22,800
95% of POWER (18.9% eff)	$ 46.5	**172**	$ 7,980
** Land Application (50%)	$ 12.5	**220**	$ 2,750

*This is not a CHP configuration where waste heat is recovered from the power generator. Rather, this HEAT + POWER configuration to maximize gasifier utilization. The fuel gas is separately supplied for heat and/or power. Power gen. is used to ballast reduced heat demand.
**Usually no more than 50% of litter can be land applied in dense production regions.

[21] Poultry Litter: 32 lb/ft^3 at 22% moisture, 6000 Btu/dry lb → 1.5 therm/ft^3. Sawdust: 10 lb/ft^3 at 5% M, 8500 Btu/dry lb → 0.81 therm/ft^3.

Observations: Displacement of only heating fuel is the simplest option for on-farm bioenergy. The use of litter for heat only balances well with the typical amount of excess litter available after land application. The gross value of heating fuel displacement is much more significant than power generation alone. The farm is not ideal for CHP, as this is a more complex configuration, and the opportunity for waste heat does not match the opportunity for maximum power generation. However, fuel gas can be diverted to meet the heat load and/or to generate power if excess gasification capacity needs to be dumped. This alternative to CHP generates the highest gross value and makes sense when the farmer is already required to own a backup generator.

Gasification efficiency has very little importance when there is an abundance of litter relative to the heating fuel need. The price and amount of displaced energy is much more important. This is because the balance of the litter is assumed to be land applied which has very little value. The economic goal is to displace as much energy (LPG) as possible and land apply the balance of the litter. Even if lower gasification efficiencies occur, this does not dramatically impact the gross income for the farm as long as the maximum amount of heating fuel is displaced. For example, if the gasification efficiency was 65% (rather than 70% efficiency) but 95% of the LPG was still displaced then the value to the farmer is the same.

The main point is that poultry litter has a higher unit value as a *biofuel* than as a soil amendment. This may not be the common perception among farmers. The typical energy value for litter is 12 MMBtu/dry ton (LHV), or about 142 gallons of LPG equivalent (LHV) per bone dry ton[22]. If converted at 70% efficiency (gasification or otherwise) the annual broiler chicken and turkey litter biomass resource potential, 10 M tons/year, equals **1-billion gallons of LPG equivalent**!

Concerns with a combustion system on the farm:

Gasification is preferable to combustion because air emissions can be more appropriately managed at reasonable temperatures and flow rates with producer gas cleaning. For example, particulate emissions would regularly be released from a litter burning furnace unless the hot combustion gases are filtered. In that case twice as much hot gas would need to be filtered with a litter combustor than with a gasification system. Secondly, ammonia evolved from the poultry litter in the combustion process would lead to high emissions of nitrogen oxides (NO_x)[23] that will be an air emission concern. Ammonia is a precursor for *chemical* NO_x, so although lean burn and staged combustion will help control *thermal* NO_x, the ammonia levels can lead to air toxic emissions concerns. The gasification process gives the opportunity to control ammonia produced in the gas phase before being delivered to a bio-gas combustor to control all NO_x emissions.

Next, the benefit of a gasification system is that a single unit could be installed to produce and distribute fuel gas to the farm at large (4 or more houses) rather than requiring the installation of many combustion furnaces with one or more located at each poultry house on the farm.

Finally, smoke from a litter combustor can contain toxic compounds including cyanide (HCN), which is a strong neurotoxin, and arsenic (As) may also be present in particulate matter! Therefore, the preferable on-farm energy system must control air toxic emissions as well as mitigating soil and water contamination.

[22] API standard is 84,500 Btu/gal LPG Lower Heating Value at 60°F

[23] Nitrogen oxides are toxic eye and lung irritants in addition to being greenhouse gases and contributing to photochemical smog (i.e., the brown cloud).

2.0 Phase II Project

Review of Technical Objectives

1. Perform bench-scale tests of a downdraft and a fluid bed gasifier to select approach for an integrated system demonstration.

Bench scale fluidized bed gasifier tests were accomplished using a 7 kW_{th} fluidized bed gasifier at Iowa State University and downdraft gasifier tests were accomplished at CPC using a test bed (operated at ~45-50 kW_{th}), built for this purpose. Our selected approach preferred development of a fluidized bed system mainly because it can use as-received[24] litter. Since neither drying nor pelletizing is required this will improve economic performance of the on-farm system (less equipment and no added biomass processing cost).

Our concept was to use lower temperature gasification (700 to 800C) in a fluidized bed to minimize evolution of alkali compounds from the poultry litter biomass. The approach to clean gas includes adding a higher temperature second stage for rapid partial oxidation and/or catalytic reforming to eliminate tars in the integrated gas production system.

The nature of the fluidized bed means that it will operate with more uniform temperatures than the downdraft, but as a result of mixing and lower temperatures it produces more tars. Regardless of this issue, the fluidized bed was favored for the poultry litter biomass application because the fuel is so difficult to convert to fuel gas without forming fused ash clinkers in the downdraft gasifier. Therefore, we chose a path that would have higher gasifier reliability. Gas cleaning became the main challenge.

Reliability (maintenance cost and down time) is one of the most important economic factors besides capital cost, and reliability will also affect customer acceptance in this new market. The fluidized bed has been shown elsewhere to have good reliability even with poultry litter fuel where clinker formation was managed with media selection and limestone injections. The fluidized bed has reduced propensity to form clinkers because it has more active and uniform temperature control. The choice of fluidizing media appears to be very important to controlling formation of sand agglomerates to avoid associated loss-of-fluidization problems. Fresh silica sand is not recommended for gasification of poultry litter. Volatile potassium evolved from the biomass ash reacts with free silica to form lower melting point potassium silicates (eutectics) that contributes to the formation of sand agglomerates in the gasifier. A mullite (aluminosilicate) or olivine (magnesium-ferrosilicate) media appear to reduce loss of fluidization problems because the silica is more tightly held in the mullite or olivine matrix. Litter feedstock that contains rice hulls for all or for a portion of the bedding may also lead to problems by adding free silica to the reaction zone, even if mullite or olivine media are used.

2. Develop a tar reformer to reduce tars to no more than 10 ppm. Explore ability of tar reformer to internally reduce ammonia concentration. Investigate other methods of post reformer ammonia reduction including Rh/Al_2O_3 catalysts at 600 to 700C.

Lower temperature fluidized bed gasification can improve reliability against agglomeration, but it also generates much higher tar concentrations by as much as 10 to 100x more than the downdraft gasifier. Tars that are formed at lower temperature may have the benefit of being

[24] "As received litter" is defined as that litter which is collected from the house floor. Preferably this litter has cake removed. This litter would have about 25% moisture and would have the consistency of sawdust.

easier to partially oxidize or reform (primary and secondary tars compared to tertiary tars) once removed from the main pyrolysis zone of the gasifier. Catalytic reforming was proposed to reduce tars, but this requires hot gas filtration to remove particulates before the catalytic reformer. Our approach involved filtration prior to reforming. A moving bed granular filter was used for particulate removal. A monolith reformer that had 95% open area metal honeycomb (fecralloy) wash coated with potassium-nickel reforming catalyst. The idea was that an open channel monolith reformer would be somewhat particulate tolerant.

The required level of tar conversion was much higher than we achieved in our test program. Tar concentrations after the reformer for the fluidized bed system were about 850 ppm in our best samples. This is approximately equal to the tar production rate of the downdraft gasifier operating on poultry litter—noting that char-air injection (secondary air) was restricted to prevent clinker formation in the downdraft. About 350 to 400C temperature drop occurred between the fluidized bed and the outlet of the moving bed filter, which impacted reformer performance. About 200C was lost in the gasifier freeboard alone. As a result, more fuel gas needed to be burned in the reformer to achieve reforming temperatures. If the filter media could be cleaned and recycled hot this would reduce heat losses from the moving bed filter.

Improved thermal integration would help increase temperatures in the reformer and help catalyst reactivity. We did add a heat recuperator after the reformer to boost thermal efficiency by preheating air to the gasifier and reformer. However, we believe other strategies should also be considered. For example, a partial oxidation stage could be added after the fluidized bed gasifier and before the hot gas filter. A partial oxidation (POX) stage after the gasifier will increase char conversion while thermally cracking a majority of generated tars. More tar cracking heat would be supplied by carbon conversion than by fuel gas combustion if close to the gasifier exit or perhaps if accomplished inside the gasifier vessel. Increased carbon conversion before the filter will improve filter efficiency, according to recent ISU study. The reformer design and approach could also be improved on to manage coking and other deactivation mechanisms.

3. Develop and test a small modular gas production module that will provide at least 450,000 Btu/hr (132 kW_{th}) fuel gas thermal energy.

The gas production module we designed will generate 450,000 Btu/hr (132 kWth) of producer gas using poultry litter as a fuel. We measured approximately 110 Nm^3/hr of generated gas. The energy content was close to 4.5 MJ/Nm^3 when using the tar reformer. This equates to over 137 kW_{th} (~469,000 Btu/hr). The top end of the gasifier was not explored and is only limited by feeder constraints and entrained media blowout

4. Develop and test a small modular power production module that will provide at least 6 kW_e and 15 kW_{th} from chicken litter in parallel with another source of AC power.

We generated 21 kWe in a Generac 035 power system using sawdust fuel in the gas production module. The power generator was connected through a back pressure regulator in parallel with a flare. This provided a nominal 7” w.c. positive pressure for the generator while the balance of gas was delivered to the flare. With poultry litter gas we generated 14 kWe in the same configuration. By the time we integrated the power generation module, our reforming catalyst had lost significant performance. As a result we did not have gas cleanliness to our minimum standards for long term operation of the engine generator. More work is needed to improve the dry gas cleanup system for the fluidized bed gasifier.

5. Operate two 175,000 Btu/hr commercial furnaces with producer gas from chicken litter in parallel with a conventional gas source such as propane.

We selected radiant tube furnaces (radiant tube burners, RTBs) for operation on the fluidized bed generated gas. These radiant tube furnaces are being implemented into more poultry houses in the United States and Canada because of improved heat distribution and improved ventilation performance. These radiant tube furnaces can also be used for brooding by adjusting the height of the burner tube. These radiant tube burners are easily modified to combust producer gas. A secondary benefit is that the combustion products are readily vented out of the poultry house. The RTB's improve bird health and increase thermal efficiency by reducing outside air ventilation requirements. The RTBs have automatic solenoid valve control operated by a thermostat, so if a flame is not achieved in a brief light period then the solenoid valve closes automatically. Venting producer gas fired burners is preferred for bird safety in the event of any system upset.

6. Test the ability of the FERCO gasifier to convert chicken litter to thermal energy.

We were not able to conduct the FERCO gasifier test because of the FERCO bankruptcy in 2002. We understand that NREL performed simulated FERCO gasification tests with poultry litter using their steam fired fluidized bed gasifier followed by a catalytic cracker. Reliable gasification was achieved when the fluidizing media was switched from silica sand to olivine.

7. Test the ability of the BECON gasifier (Iowa Energy Center/Iowa State University) to convert chicken litter in to thermal energy.

The BECON gasifier is an 800 kW_{th} air blown bubbling fluidized bed. This gasifier was operated on poultry litter in 2002. The generated gas quality was lower than on other biomass feedstocks. No bed freezing was observed in the BECON gasifier. Silica sand was used as fluidizing media, but it had been aged with other biomass feedstocks and previous limestone injections.

8. Conduct a 6-wk test (one growth cycle) of a small modular biopower system that has been integrated with a chicken house at the University of Arkansas broiler production research facility.

The University of Arkansas broiler production research facility was quarantined during the time of our planned demonstration due to reportable avian diseases. The demonstration was moved to Community Power Corporation's Littleton facility and held in Mid May 2004. Industry representatives were in attendance along with a representative of the University of Arkansas.

9. Prepare a business plan for a litter management services company.

Economic analyses were performed as part of the development of a business plan to commercialize on-farm litter to energy systems.

Task-1: Develop project plan and schedule.

The phase II project was organized by task and milestones, with the main goal to produce an integrated system suitable for field demonstration.

Task	Description	Associated Milestone/Significance
1.	Develop project plan and schedule	No milestone for this task.
2.	Select on-site system configuration	**(A.)** Selection of the design configuration for the integrated demonstration. /First US-sourced small modular system for on-farm conversion of chicken litter into useable energy.
3.	Demonstrate FERCO system on poultry litter	**(B.)** Analyze results from FERCO testing. /Tests the ability of a near-farm system to be able to receive excess litter from a cluster of farms for distributed power generation.
4.	Develop/build integrated system for on-site demonstration	**(C.)** Complete testing of tar reformer. / Necessary to produce clean gas for an integrated system demonstration
		(D.) Complete testing of ammonia reduction reformer. /Secondary importance to tar reformer, but necessary to control nitrogen oxide emissions.
		(E.) Design and Build the Integrated System/ The overall goal of the project is to build an integrated pilot gasification system.
		(F.) Complete preliminary testing of integrated system. Achieve cleaned producer gas suitable for firing in a commercial brooder. /Necessary to provide fuel gas to commercial brooders to maximize the potential for fuel gas delivery.
5.	Demonstrate integrated system operating on poultry litter	**(G.)** Complete field demonstration. /First US based on-farm system to convert poultry litter in to usable energy.
6	Interact with industry advisory group	No milestone for this task./ Purpose was to achieve visibility in the industry and recruit interest for phase III.
7.	Prepare system documentation	**(H.)** Complete documentation package. /Purpose was to enable replication once acceptable performance was achieved.
8.	Prepare business plan	**(I.)** Complete business plan to attract investors to participate in a phase III deployment /First ever description of a highly replicable commercial operation able to sell, or own and operate, distributed energy equipment that can convert poultry waste into a number of usable high value end products.

9.	Reporting	No milestone
10.	Project Management	No milestone.

Task-2: Select on-site system configuration

The purpose of this task was to make a down select between competing gasification and gas cleanup technology options. The conversion of biomass to fuel gas begins with gasification. The type of gasification technology affects requirements for fuel preparation, gas cleanup, and also the maintenance and reliability of the gasifier itself. The main challenge with poultry litter gasification is its strong tendency to form clinkers at gasification temperatures—affecting gasifier reliability and operating costs.

Downdraft Gasifier Tests

The open top downdraft gasifier is configured such that biomass feedstock enters the top of the gasifier along with and in the same direction as the main reaction air. Air can be separately delivered above and below a flaming pyrolysis zone as shown in the diagram. Above the flaming pyrolysis zone is fresh biomass and below it is glowing hot charcoal. The flaming pyrolysis zone is a narrow band that propagates upward from a glowing hot charcoal bed toward the fresh biomass feedstock. Within the flaming pyrolysis zone, most of the volatile matter is released from the biomass particles, leaving mostly fixed carbon. Secondary air, or what we call "char-air", is injected below the flaming pyrolysis interface into the hot charcoal bed. Adding air to the charcoal bed increases the char-zone temperature and helps aid conversion of char into gas. The char zone provides surfaces area useful for heterogeneous reaction with tar and pyrolysis oils. Without the addition of char-air, the charcoal would be air starved and would cool under endothermic reaction conditions. The conversion of tar through the hot charcoal bed can be idealized as a plug flow reactor (no back mixing). The downdraft gasifier is essentially two stage gasification (flaming pyrolysis + char gasification) that normally yields low tars (~100 ppm).

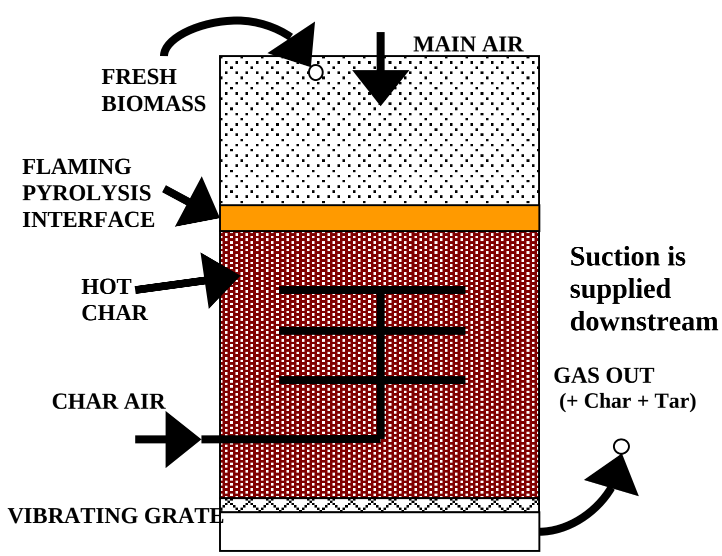


Figure 11 Diagram of a Downdraft Gasifier with two stages of air injection (main and char-air)

Gas cleanup is quite simple when the downdraft gasifier is operated successfully. Gas cleaning requires no more than cooling and dry filtering at ~100C when the raw gas has less than 100-ppm tars. The dry filtering process has been shown to reduce tars by ~ 4 fold to less than 25-ppm if the raw gas contains a sufficient amount of residual carbon in the charcoal dust. The tar reduction effect is somewhat dependent on the method of cooling and quality of the entrained charcoal dust.[25] The immediate challenge with poultry litter gasification in the downdraft is that the charcoal yield after pyrolysis is much lower. Therefore, higher ash concentrations in litter char compared to woodchip char means that there is reduced opportunity for insitu tars conversion. Also, the ash softening point (or go/no go peak gasification temperature) is 100 degrees or more lower for poultry litter because of higher alkali mineral concentrations (i.e., potash). There is therefore an increased probability of gasifier failure by ash fusion.

Lower char yields after pyrolysis means that the char residence time must be reduced with more aggressive grate agitation to avoid clinker formation. This rapid movement of the charcoal bed downward means that a more rapid pyrolysis flame front propagation upward is required to balance the gasifier—that is required to stabilize the gasifier without causing the flame front to also drop. The reduced char budget—i.e., the volume of mostly fixed carbon char between the grate and the pyrolysis front—directly impacts the extent of tar conversion that can be achieved in the air-stoked charcoal zone. The practical limit of char residence time is complete carbon conversion. Clinkers are formed and maximum temperatures occur when the extent of carbon conversion approaches to close to its physical limit inside the gasifier. Therefore, the char/ash product must be removed with about 50% residual fixed carbon. This residual carbon content is also important for dry filtration by acting as adsorption media of tar residuals. Bed "freezing" is phenomenon related to clinker formation that occurs when the char zone temperature rises above the ash softening point. Both issues are a concern for gasification of high ash poultry litter in the downdraft gasifier because peak operating temperatures can exceed 950 or even 1000C.

New Poultry Litter Pellets for the Downdraft Gasifier

In our phase-I tests we used commercial ¼" pelletized litter, where pellets are pressed at 50,000 psig. We found that the flame front did not propagate readily into the fresh fuel interface in the normal downdraft configuration. We had to reduce the superficial velocity of the main air to help flame front propagation. This observation basically means that the dense litter pellets did not light well at the flaming pyrolysis front until we reduced the main air superficial velocity. If the flame front propagates too slowly, then this impacts the air/fuel equivalence ratio and pyrolysis temperature. Adding more char-air (below the flame front) helps raise the flame front by increasing the char zone temperature, but the maximum char temperature is limited by the ash softening point. The design impact of slow flame front propagation is that the gasifier has a shorter aspect ratio (length/diameter) and lower specific gasification rate (kg/hr/m^2).

New litter pellets were tested in phase II to help improve flame front propagation. Warren & Baerg produced lower density pellets using their "cubing" technology (16,000 psig). These

[25] CPC has demonstrated as low as 5 ppm tars after the filter using wood chip fuel. The Danish Technical University has shown a similar effect when using straw or woodchips in their 2-stage Viking gasifier.

"cubes" were larger (0.75" diameter x 1" long) with lower density than the ¼" pellets tested in phase I. The litter was also mixed with 1% limestone to mitigate sintering of the char bed.

Table 7 Downdraft gasifier tests (12" diameter), new litter pellets from Warren & Baerg ¾" round

Test	Average Gas Composition (dry %)					LHV* MJ/Nm^3 (Btu/scf)	Temp °C		Notes
	O_2	CO	CO_2	CH_4	H_2		Grate	Out	
1	1.2	22.1	9.9	0.9	13.6	4.59 (123)	818	725	25 Nm^3/hr gas flow passive char-air injection
2a	0.8	17.4	11.4	0.9	14.0	4.03 (108)	946	792	30 Nm^3/hr, restart on PL passive char-air
2b	0.7	17.9	11.5	1.7	14.6	4.16 (112)	940	823	20 Nm^3/hr, T4>1100! blocked char-air
3	0.1	19.6	12.8	2.1	16.2	4.98 (134)	800	772	35 Nm^3/hr, bed sintered blocked char-air
4	0	18	12	2.0	15	4.6 (124)	910	715	~20 m3/hr, no char-air tree Flame front dropped!

Dry gas value (typical); reference STP conditions = 1 atm, 0 C (22.4 m^3/kmol)

The new lower density pellets showed some promise for increased flame front propagation. Still, char production was low. Tests in the 12" diameter gasifier showed the best gas quality at 35 Nm^3/hr flow rate. However, this same test was eventually shut down because char began to sinter below the flame front. Post mortem showed that the carbon content was very low in any char particles. Based on test #1, which was operated successful at 25 Nm^3/hr (32 kWth), it is estimated that the farm-scale system would need to be 48" diameter or more to meet the peak 500 kW_{th} gas production rate (1.7 MMBtu/hr). Subsequent tests showed that restarting the gasifier on poultry litter char (residual from previous run) lead to a variety of operational problems including "rat-holing", grate over temperatures, and bed freezing (i.e., char sintering).

Table 8 Tar and Particulate results for Downdraft on Warren and Baerg ¾" Poultry Litter Cubes

Test # 3 Gas sample at 2 hr 10 min	Results (mg/Nm^3)	*ppm (weight) MW = 26 kg/kmol
Gas Sample (STP)	9.51 L	
Tars	**1,020**	**878**
Particulates (>0.7 µm)	2,193	1,889
Ultrafines (<0.7 µm)	641	552

*ppm (weight basis) = mg tars/(kg clean gas + kg tars)

Char air injection was severely restricted to prevent over temperatures in the gasifier. On the other hand, char air injection is necessary to help flame front (FF) propagation upward and to reduce tars. The lower density W&B litter pellets did improve the FF propagation rate somewhat so that 30 m^3/hr gas production could be achieved in a 12" diameter gasifier, rather than in an 18" gasifier. Still the FF rate was not high enough to allow much char air necessary for attaining low tar yields. A somewhat related issue was that the removal of char from the gasifier was not high enough to prevent approaching the carbon conversion limit.

In summary, the stable operating window for the downdraft gasifier on poultry litter was very small and prefers a relatively large diameter gasifier to keep the pyrolysis superficial velocity low and flame front propagation rate high. The next step, or future research, could explore even lower density pellets to help increase the FF propagation rate to help achieve higher superficial velocities and higher char yeilds. Tailored grate design for poultry litter and modified control development would also be required to adapt the removal rate of char to the desired char production/removal rate. Much time and expense would be required and we determined that this was well beyond our budget and scope of work. Finally, fuel processing costs would also impact the overall system economics, even with the potentially lower capital cost of the downdraft. Ultimately, it was decided that the benefits of the simple downdraft technology could not be realized when using poultry litter fuel without substantial development cost, time and effort.

Bubbling Fluidized Bed Gasifier Tests

The Center for Sustainable Energy Technologies at the Iowa State University performed multiple poultry litter gasification experiments on behalf of Community Power Corporation. Lab-scale gasification tests were performed in the (nominal) 7-kWth fluidized bed gasifier located in 1056 Black Engineering on the ISU campus. This lab-scale gasifier was designed to have a fuel feed rate of 2 to 5 kg/hr (4 to 10 lb/hr). The diameter of this gasifier is 4” (inside), and the dense phase of the bed is usually maintained at about 8-inches in height (2-1 aspect ratio). This reactor is equipped with heaters for the reaction zone and freeboard to control heat loss. Therefore, the lab-scale reactor can model either adiabatic operation or certain off-equilibrium states. (Air/fuel equivalence ratios can be adjusted independent of temperature within a small range).

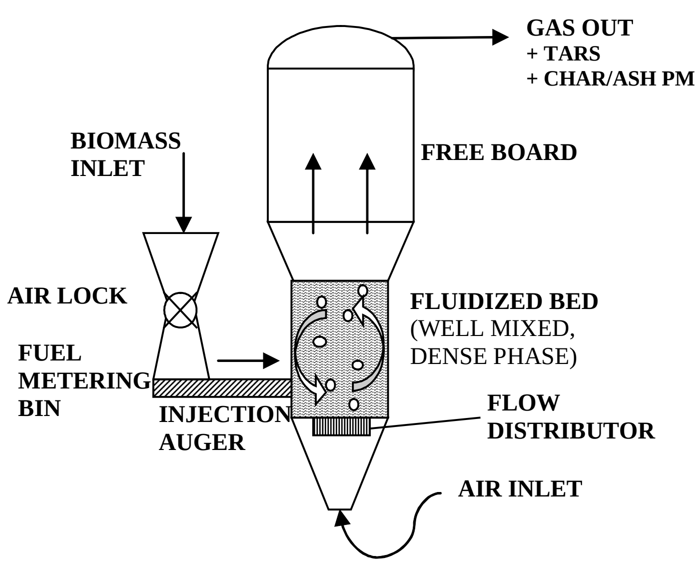


Figure 12 Diagram of a Bubbling Fluidized Bed (BFB) Gasifier. Characteristics include a well mixed reaction zone that has less than 2% biomass mixed with hot fluidized bed media.

Six experiments were performed in ISU's lab-scale fluidized bed gasifier to explore tar yields with temperature and to explore incidental bed agglomeration when using fresh silica sand as fluidization media. Tar measurements were taken using the IEA Tar Protocol v2.1.[26] An overview of each experiment is given in Table 9.

Table 9 An overview of the six experiments performed in the 7 kWth system.

Test #	Date	Avg. bed temp	**Equiv. ratio	Tars (mg/Nm^3)	Agglomerates in bed?
1	1/9/03	725 °C	0.30 – 0.45	16,700	Not observed
3	1/14/03	725 °C	~ 0.41	12,000	Yes – soft/weak
2	1/12/03	800 °C	~ 0.41	7,400	Yes – soft/weak
5	8/4/03	670 °C	0.30	21,300	Yes - hard
4	7/29/03	725 °C	0.30	20,160	Yes - hard
6	8/27/03	800 °C	0.30	16,000	Yes - hard

* determined by distillation. **Equivalence ratio is the actual air/fuel ratio divided by a reference air/fuel ratio for stoichiometric combustion. ***data reference STP 0C, 1 atm.

In tests 4-6, the bed was given sufficient time during the start-up combustion period for complete calcination of the limestone. The system was allowed to come to steady state gasification before collecting the tar sample. Tar sampling typically lasted one hour. In all cases the tar concentration was determined by distillation. The evaporative method is more commonly reported in literature, but this method tends to under predict actual tar concentrations.

Each test (exept #1) was conducted with fresh silica sand media. The bed media is a mixture of 85% silica sand and 15% limestone. The silica sand was 30 x 40 mesh (~420-590) particle size, and the limestone was 20 x 30 mesh (590-840 micron). No sand or limestone is added during the test. The bed is preheated with the hot air and clamshell heaters on the bed. Solid fuel combustion is used to finish heating the bed to the desired operating temperature.

It is notable that test #1 was used for shakedown testing, and consequently did not include fresh media. It was observed that the aged silica sand (used in other biomass gasification tests) did not have the same agglomeration tendency as the other freshly prepared silica sand media. We don't know for certain how much this aging effect helps to stabilize the silica media or why. No evidence of bed agglomeration was observed during the test period, although the test was short (just a few hours). All other tests that used fresh silica showed operational evidence of bed agglomeration with in a few hours (temperature gradients in the bed) that was also confirmed by post mortem inspection.

[26] IEA Tar Protocol: www.tarweb.net

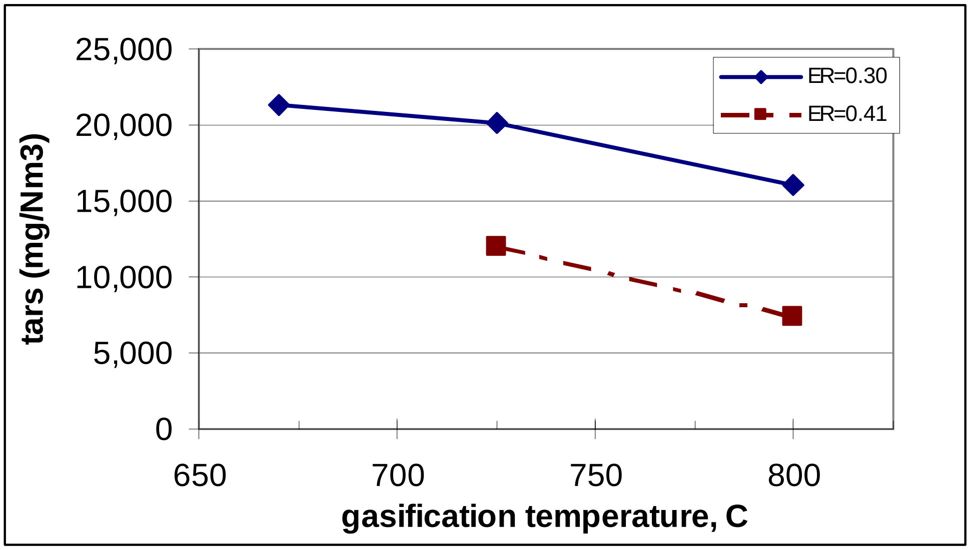


Figure 13 ISU Lab-scale gasification tests on Poultry Litter show a logical trend. Higher temperatures and higher equivalence ratios result in lower tar yields.

Gasification conditions for tests 1-3 were atypical of normal gasification. However, these results may still offer insight on the gasification of poultry litter. [Figure 14] High equivalence ratios for tests 1-3 result in lower tar yields compared to normal gasification conditions (tests 4-6). The implication is logical: increased oxidant concentrations results in lower tar yields at a given operating temperature. A practical example of high equivalence ratios might occur in a reactor *with extensive heat loss* or when utilizing higher moisture fuel so that more air is required achieve the target operating temperature. The opposite condition of low equivalence ratio operation (below 0.3) could occur in a gasifier with indirect heating or somewhat with gasification air preheating. Limited oxidant during indirect gasification seems to increase tar production at a given operating temperature and excess oxidant seems to reduce tars.

Basic gas compositions were recorded using a NOVA portable gas analyzer and, when available, a gas chromatograph provided additional details for C1 and C2 concentrations, as well as confirming evidence of the balancing nitrogen content. Average gas compositions over the duration of the experiments are reported in Table 10. Review of tests 4-6 suggests that gas composition and heating value improves as the reaction temperature increases. The higher heating value of the gas, on a dry, tar-free basis, for Test 6 is approximately 5.4 MJ/Nm^3 (145 Btu/scf). The lower hydrogen yield recorded in tests 1-3 may also be an indicator of lower fuel quality in the gas, but no data for methane or ethylene concentrations was available in these tests.

Table 10 Bulk gas composition during litter gasification experiments in the 7-kW_{th} gasifier.

	H_2	O_2	CO	CO_2	CH_4	C_2H_4	FB Temp	LHV*	LHV*
Test	Nova	Nova	Nova	Nova	GC	GC	°C	MJ/Nm^3	Btu/scf
1	6.9	0.3	8.1	17.3	n/a	n/a	725°	--	
3	6.3	0.0	8.8	18.0	n/a	n/a	725°	--	
2	7.2	0.3	8.4	17.0	n/a	n/a	800°	--	
5	10.7	0.0	9.4	20.0	2.8	1.3	670°	4.11	110.4
4	12.2	0.0	11.8	18.4	3.0	1.5	725°	4.77	128.0
6	13.4	0.0	14.4	17.0	2.9	1.8	800°	5.37	144.1

*LHV reported on a dry, tar free basis; STP = 0C, 1 atm.

Milestone-A: Down-select Gasification Technology for Pilot System

The fluidized bed gasifier was preferable for our pilot-scale poultry litter gasification system for two basic reasons. First, little or no fuel preparation is required to utilize poultry litter in the fluidized bed gasifier other than cake removal (sieving). Second, the fluidized bed gasifier has the potential for higher reliability when using poultry litter compared to the downdraft gasifier because it can be operated at lower and more uniform temperatures than a practically sized downdraft gasifier.

No fuel drying is required for raw litter fed to the fluidized bed gasifier because the as-received feedstock will usually be less than ~25% moisture. Sieving to remove cake is recommended. Cake should be ground before being fed. In contrast, some feedstock drying would be required as well as some densification required to utilize biomass in the downdraft gasifier. We have not tried to use raw litter (without cubing) in the downdraft; however, this approach could be attempted at some point in the future. Based on farm-scale cubing technology, feedstock preparation cost for the downdraft would be more than $20/ton and therefore becomes a significant economic consideration.

It is important to note that aged silica sand did not show the same tendency to agglomerate even after several hours of operation, whereas fresh silica sand did show a high tendency to agglomerate. Although bed freezing was observed in the Iowa State lab-scale gasification tests, their selection of silica sand may be implicated as a possible contributor to rapid bed agglomeration with poultry litter. The presence of free silica will react with volatile potassium at gasification temperatures to form low melting point potassium silicate eutectics on the surface of the sand particle. The presence of both free silica and volatile potassium gives the potential for bed agglomeration. Poultry litter has nearly 5% potash in the dry biomass. Addition of limestone is theorized to stay the onset of agglomeration by controlling sulfur and chloride concentrations in the gasifier that contribute to alkali mobility.[27] Limestone adds calcium oxide (post calcination) to the reactor which may stabilize silica in other ways. T.R Miles technical consultants reported 2-wks of reliable gasification of poultry litter and swine manure mixes in the

[27] Conversation with T.R. Miles technical consultants (May 2004) regarding alkali control and bed agglomeration.

EPI pilot gasifier at 815C when aged silica sand was used without any added limestone! Over-fire air was added in the freeboard to immediately combust the generated gas inside the gasification vessel and so no cleaning or distribution of the gas was attempted.

NREL performed steam gasification tests on poultry litter in their lab-scale fluidized bed gasifier. They also found that fresh silica sand rapidly agglomerated when using poultry litter feedstock. However, when the operator changed the fluidization media to olivine, no further problems with bed agglomeration occurred. Olivine is a naturally occurring ferro-silicate mineral with silica more tightly held in the mineral matrix. Another option for media selection is to use high alumina mullite sand instead of pure silica sand. Mullite is a manufactured material comprised of aluminosilicate compounds. High alumina based mullite sands are available, but mainly the silica is believed to be more tightly held in the mullite matrix and therefore has a lower potential to react with vaporized potash.

Task-3: Demonstration of FERCO Gasifier on Poultry Litter

The FERCO gasifier was invented at a DOE laboratory based on a fluid catalytic cracker with regenerator system that is commonly used in the petroleum industry. This technology is a method of supplying indirect heat for steam gasification of biomass to produce synthesis gas. Steam-biomass gasification and charcoal-air combustion are conducted in two separate vessels with hot sand circulating between each vessel as a heat carrier.

We reported to the DOE that the FERCO gasification tests could not occur because the Future Energy Resources Company (FERCO) was in the process of filing chapter-11 bankruptcy protection. We reported that our new system approach would likely require a hot gas filter, and that this component would be substantially more expensive than our original equipment cost estimate. CPC requested a no-cost modification to our project if we could add a task to review appropriate hot gas filtration technologies for our system and perhaps purchase a hot gas filter if needed. The FERCO gasification test was therefore cancelled with the approval of our DOE contact. We added a task to investigate hot gas filtration technology options for our pilot scale system and eventually purchased a moving bed granular filter for the pilot scale research gasifier. Our selection of the fluidized bed gasifier technology for poultry litter required a novel approach to gas cleanup that involved the need for hot gas filtration.

Task-4: Develop/Build Integrated System for Demonstration

Hot Gas Cleaning Need for the Fluidized Bed Gasifier

Biomass gasification produces mainly permanent gases (H_2, CO, CO_2, CH_4, C_2H_4) with lesser amounts of particulate matter (ash and char particles) and tars. Some light weight hydrocarbons are also produced in minor amounts such as toluene that are not usually quantified as tars, even though condensable. Gas samples are collected at 0C which condenses heavy tars and light hydrocarbons and water. Basically, the particulate free residue that remains in a sample jar after solvent (e.g., acetone) distillation is classified as “tar”.

Biomass is comprised of cellulous and hemicellulous polymers plus lignin, which provides structure to the biomass. Biomass tars are generally acetone soluble and are believed to form as a result of thermal cracking of lignin. Examples of these high molecular weight tar compounds include naphthalene, phenanthrene, fluoranthene and pyrene. Water is also present in the raw gas with a dew point of ~ 40 to 50C (8 to 12% M). Tar compounds represent the most difficult and undesirable component in raw biomass producer gas. Tar compounds will rapidly convert to gas and soot at high temperatures (>1000C) with short residence times (<1 s). However, the softening point for biomass ash/char makes gasifier operation near this temperature quite impractical for reliability. The limited peak operating temperature of a biomass gasifier is even more important when considering high alkali poultry litter.

Dry filtration of biomass producer gas can be accomplished if tar concentrations are less than about 100 mg/Nm^3, in which case standard bag filter materials (polyester or PTFE membrane lined polyester) can be used at ~100C. This "cold" filtration can occur with "wet gas" since it is filtered above the water vapor dew point. If tar concentrations are higher than ~100 mg/Nm^3 then a sticky cake will form on the bag filter that will cause unacceptable pressure drops over a very short period of time. The raw gas from the fluidized bed gasifier will be on the order of 10,000 to 20,000 mg/Nm^3, therefore, some form of extensive tar conversion is needed before dry filtration can occur. On the other hand, if catalytic methods of tar conversion are used, these usually require particulate removal from the hot gas before catalytic conversion. Since the tar dew point could be as high as 400°C, a method of particulate removal from the hot producer gas is needed. Catalytic reforming should occur at about 850°C (to prevent sulfur poisoning) so the raw gas should be filtered at the highest possible temperature immediately after exiting the gasifier.

As we endeavor to assemble a dry gas cleanup system (no wet scrubbers) for the on-farm litter to energy system, we have two options: (1) extensive partial oxidation or high temperature thermal cracking of tars immediately after the gasifier and/or (2) hot gas filtration followed by catalytic reforming. The design for option (1) has yet to be developed. Option (1) should be considered as an important part of any future system development. Option (2) was viewed as a practical and direct approach to developing a successful dry gas cleanup system within the project time-line. An acceptable, low cost method of particulate removal at elevated temperatures (above the tar dew point) was needed to access option (2).

Milestone B: Brief Review of Hot Gas Filtration Technology Options

This milestone was created to replace the FERCO gasification tests on poultry litter. Hot gas cleaning is an essential part of developing a dry gas cleanup system for the fluidized bed gasifier.

As we began to review the options for hot gas filtration, it became very clear that the filter could be one of the most expensive components of the farm-scale gasification system. In fact, candle filters are so expensive that they are cost-prohibitive for the farm-scale application. The commercial options for hot gas filtration are very few and basically include either ceramic or metal candle filters. There was only one potentially affordable alternative called a moving bed granular filter (MBGF). The MBGF is an R&D technology invented at the Iowa State University that is nearing commercialization with exclusive license status presently residing with Energy Products of Idaho. Table 11 summarizes hot gas filter options evaluated for the on-farm gasification system

Table 11 Hot gas filtration options and cost estimates

	Description	Point of Contact Or Vendor	Ref #	*Pilot Quote ($)	**Farm Scale Cost ($)
1	Nextel Fabric Bag House 760°C cont, 99.9% eff	3M Corporation Tim Gennrich	Discontinued	N/A	N/A
2	Ceramic Composite Candle Filters (CCCF), 99.99% eff	McDermott Richard Wagner	Discontinued	N/A	N/A
3	HyPulse GSV Filter (HastelloyX metal candles) 700°C, 99.9% assumed	Mott Corp. Glen W. Brown	Quote: E118119AW	$145,000	$266,000
4	Blow-back, Iron Aluminide Candle Filter (mat. option) 700°C, 99.99% efficiency	Pall Corporation John Sawyer	Quote: 03-0016	$122,750	$225,250
5	Blow-back, Ceramic SiC candle filter system, 700°C, 99.99% efficiency	Pall Corporation/ John Sawyer Schumacher GmbH Elements	Quote: 03-0016	$118,950	$218,250
6	Blow-back SiC candles Custom engineered 730°C, 0.1 μm (99.9%)	Custom Design: Eric Simonson Refractron Elements	Quote: 28015-100	$111,000 (150 Nm^3/hr)	$178,000
7	**Moving Bed Granular Filter** (ISU Design) 99% efficiency, 750°C	Energy Products of Idaho (EPI) Paul Logan	Ref Quote: 03519A	**$33,990**	TBD

*Size: 120 Nm^3/hr producer gas, unless noted. **Estimated at 330 Nm^3/hr by 0.6 power law.

The blow back (back pulsed) ceramic and metal candle filters for the pilot scale (~120 Nm^3/hr) would cost between $111,000 and $145,000. This single piece of equipment could cost more than we budgeted for all equipment in our pilot-scale system. The blow back filter costs for the farm-scale (330 Nm^3/hr) are estimated to exceed the cost target for the entire bioenergy system. Ceramic or metal candle filter elements comprise about 50 to 60% of the capital cost at the small scale and are by themselves are too expensive for this application.

We were apprised of two potential filter options besides blow-back candle filters. One of these options was the continuously woven ceramic bag filter (3M Nextel fabric technology), item 1 in the table above. The Nextel fabric is commonly used for fire protection equipment. The high temperature filter material is made of flexible boron modified mullite continuous woven fibers (62% alumina, 24% silica and 14% Boron oxide). The material does not lend itself to stitching or seamed construction especially if operated at elevated temperatures. Therefore a continuous tubular weave was essential for a hot gas filter application. At one time 3M manufactured a continuously woven seamless tube of high temperature Nextel fabric for the hot gas filter market. This woven ceramic fiber bag had a continuous operating temperature of 760C, and would have been a lower cost alternative to ceramic candle filters. A back-pulsed hot bag-house system designed by Fisher and Klosterman was installed at NREL in 1992 and used to filter pyrolysis vapors. CPC discovered that although the Nextel fabric is still manufactured, the continuously woven socks are no longer offered by 3M and the looms for the tubular product have been decommissioned. Even though there is little competition in the hot gas filter market today, there was insufficient market demand for 3M to continue the offering.

The lowest cost filter option we found was the Moving Bed Granular Filter. This technology is elegant in its simplicity. The filter uses inexpensive ¼ x $^{1}/_{16}$ gravel as filter media that can be purchased from most local aggregate companies for about $5/ton. The filtration principle relies on the fact that a dust cake will deposit at the engagement interface of a packed bed and this dust cake develops into a fine particle filter. Pressure drop is managed by slowly and continuously removing media from the bottom of the filter with an auger along with collected dust. This media removal process concomitantly replenishes the dust collecting interface with fresh media and controls pressure drop. The novelty of the invention is a method of disengaging the gas from the media without disturbing the fixed bed of gravel. Recent data for coal fly ash showed nearly 100% filter efficiency for particles in the size range 3 to 18 μm. The filter efficiency was also quite good for larger particles (>181 μm), but medium size particles did show some slip in the size range 33 to181 μm. The demonstrated overall efficiency was close to 99% for coal fly ash.

CPC made a commitment to purchase the MBGF from Energy Products of Idaho for <u>~$34,000</u>, who had recently purchased an exclusive license to the technology in 2003. The filter itself consists of a simple stainless steel vessel with a sleeve insert. A second comparative quote for the same equipment would be less than <u>$15,000</u> if we purchased it from a local ASME code certified weld shop. We assume that in the future the price for a farm-scale moving bed filter could be significantly reduced with a volume purchase order. Our target price for a larger farm-scale (330 Nm^3/hr gas at 750°C) MBGF including media cleaning screens and automated recycling is $47,000, with a production purchase order of 10 to 50 units.

The $34k we paid for the moving bed filter did not include a media cleaning and recycle system. This media cleaning and recycle task was performed manually to save equipment cost. We found that a vibrating screen worked very well to remove the majority of collected particulate matter from the granular filter media. We used a simple rock tumbler connected to a shop vacuum cleaner as a final media cleaning step. Perhaps a small fluidized bed would also work well in an integrated system. The granular media removal and recycle rate is very small, approximately one gallon of media per hour, so the media cleaning system could be quite small and low cost. Our project could not afford any other hot gas filter option and so we chose the research grade MBGF.

This project afforded the opportunity to achieve the world's first integrated system with a fluidized bed biomass gasifier with a MBGF and an open channel monolithic tar reformer for gas cleaning.

<u>Milestone C: Complete Testing of Tar Reformer</u>

During the summer of 2002, CPC investigated catalytic reforming of tars using noble metal catalysts. The catalyst is used to convert tars to gas and soot at ~800°C. This catalytic reforming effort benefited another project: phase IIb USFS-NREL small modular biopower program. The information was also useful to system development for this Phase II SBIR. No filter was installed upstream of the monolithic reformers, only a high efficiency cyclone. The catalytic reforming tests presented in this section were performed using wood-gas generated in the downdraft gasifier fueled by woodchips. Sud-Chemie/ ProtoTech supplied 25 cpsi (cell per square inch) square channel ceramic monoliths, 5.7" diameter x 3" long, wash-coated with either Pt/Pd or Pt/Rh catalysts. CPC assembled these disks and fixed them into a 6" stainless steel tube using 1/8" thick Fiberfrax 550 paper as a compressible radial spacer. Most experiments were performed at a total flow rate of ~50 Nm^3/hr producer gas. Air was added upstream of the reformer to control the reformer exit temperature in the range 800 to 850°C.

Table 12. Pt/Pd catalyst (Sud-Chemie/ProtoTech) on 25 cpsi Zirconia Monolith, 5.66" dia x 6"L

Date	Exp #	Flow Rate	Aux air	Tave	tar in	tar out	% tar X
		Nm^3/hr	%	°C	ppm	ppm	
8/26/2002	21	50	7.0%	791	263	91	65%
		58	6.7%	840	248	133	46%
	22	51	7.1%	778	68	17	75%
		51	7.1%	782	179	109	39%
		57	6.6%	820	158	115	27%
8/29/2002	23	53	5.3%	838	36	6	83%
		53	5.3%	833	135	95	30%
		53	5.3%	836	97	69	29%
	Averages:	**53**	**6%**	**815°**			**49%**

Table 13 Pt/Rh catalyst (Sud-Chemie/ProtoTech) on 25 cpsi Zirconia Monolith, 5.66" dia x 6"L

Date	Exp #	Flow Rate	Aux air	Tave	tar in	tar out	% tar X
		Nm3/hr	%	°C	ppm	ppm	
9/3/2002	24	48	8.6%	782	202	22	89%
		48	8.6%	786	497	58	88%
9/4/2002	25	51	8.1%	816	372	86	77%
		51	7.9%	808	1042	303	71%
		51	8.0%	813	592	194	67%
		48	8.4%	820	770	220	71%
	Averages:	**50**		**804°**			**77%**

Table 14 Pt/Rh catalyst (Sud-Chemie/ProtoTech) on 25 cpsi Zirconia Monolith, 5.66" dia x 12"L

Date	Exp #	Flow Rate	% air	Tave	tar in	tar out	% tar X
		M3/hr		°C	ppm	ppm	
9/9/2002	26	53	8.0%	798	518	192	63%
		51	3.3%	792	227	60	74%
		49	4.6%	798	205	87	58%
9/10/2002	27	52	7.4%	796	223	32	86%
		51	5.6%	780	219	43	80%
		50	4.5%	778	184	47	74%
9/11/2002	28	50	5.0%	781	236	25	89%
		51	4.2%	796	409	110	73%
		51	3.9%	797	371	115	69%
		51	4.4%	786	349	108	69%
	Averages:	**51**	**5%**	**790°**			**74%**

In general we found that there appeared to be no useful correlation between tar conversion and either the reformer exit temperature or average reforming temperature. The platinum/rhodium catalysts seemed to perform better than the platinum/palladium catalysts, at least initially. Increasing the reformer length did not necessarily seem to improve the performance, which may imply a mixing issue in the laminar flow channels.

We observed a generally decreasing catalytic performance within a given day of operation (ash would begin to deposit at the inlet of the catalytic reformer with time). The deposition of biomass ash at the reformer inlet emphasizes the need to use a more efficient hot gas filter before the monolith tar reformers in the fluidized bed gasifier. (No filter was used, only a cyclone.) We also observed a longer term decrease in catalyst performance with cumulative time on stream. Some deactivation could have been due physical blocking of active channels with the deposition of ash at the catalyst inlet, but also there could have also been a progressive poisoning perhaps due to sulfur.

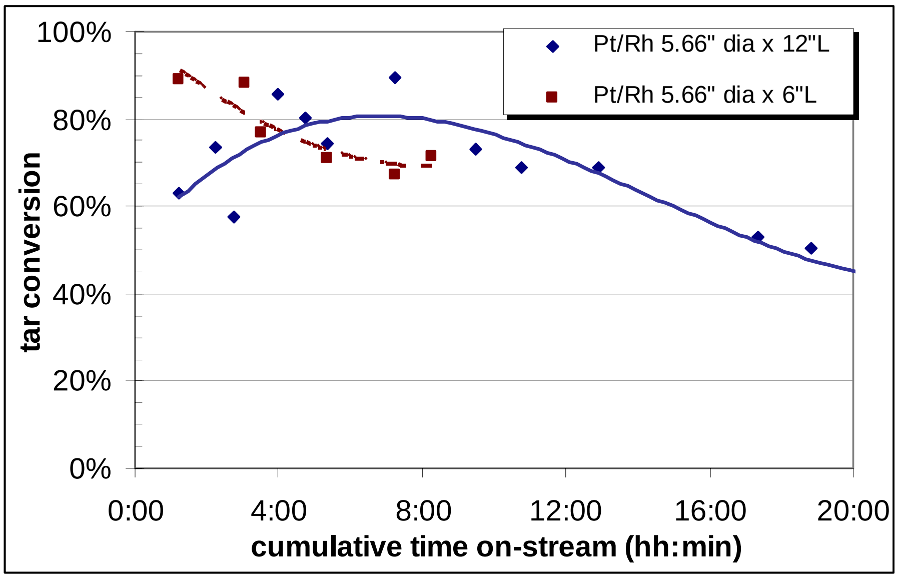


Figure 14 Plot of biomass tar conversion as a function of cumulative time on stream

All tar measurements were taken using a vapor phase sampling system that rapidly quenched the sample to 0C. The sample tubes and filters were rinsed with acetone and the rinsate collected in sample bottles. After distillation, the residue in the sample bottles was quantified using gravimetric analysis and the total concentration of tars was calculated using the known quantity of gas sampled and its molecular weight.

Detailed results came by tar speciation analysis using NREL's molecular beam mass spec (MBMS) instrument. A tar sample taken on 9/11/2002 showed that certain compounds were completely destroyed, such as acenaphthylene and bezo(g,h,i)perylene and indeno(1,2,3-c,d)pyrene; while other more compact molecules were converted on the order of 70 to 85%. Pyrene was the most recalcitrant compound with only 50% destruction observed.

Milestone D: Trace Contaminant Analysis Results

For our integrated system we chose a nickel catalytic reforming catalyst because it is known to reduce ammonia concentrations while also reducing tar concentrations. We did not achieve quantitative results for ammonia reduction on the nickel catalyst when using poultry litter generated gas. The main effort was to achieve low tars, and in the end we were still in the pursuit of this primary goal. Data presented later in this report shows that we achieved about 80 to 90% reduction in tars from poultry litter gas, but our need was 99.5% to 99.9% tar conversion. It would be more instructive to measure the reduction in ammonia under the same conditions that we would used to achieve low tar gas in our system.

Trace contaminants were measured during the BECON gasifier tests on poultry litter. Three different operating conditions were investigated during this experiment. The first condition is air blown gasification of poultry litter with 675C operating temperature. The second operating state was air blown gasification at 675C with saturated steam added at the rate of 15 kg/hr to see if there was any benefit to litter gas quality. The third operating state was air blown gasification at 870C (no steam addition).

Accurate trace contaminant sampling from biomass gasification product gas is not a trivial task. The highly soluble nature of ammonia complicates wet chemistry sample preparation and analysis. Also, the highly reactive nature of hydrogen sulfide makes its accurate quantification a challenge. Drager tubes were used to quantify hydrogen sulfide while wet-chemical methods were employed for ammonia quantification. The data in Table 15 is listed in the order the samples were collected. All concentrations are reported on a dry, tar-free, volumetric basis.

Table 15 Trace contaminant quantification results, BECON gasifier testing of Poultry Litter.

Test Conditions	NH_3 Concentration*		H_2S Concentration (ppmv)	
	μg/L	Volumetric %	Before NH_3 Test	After NH_3 Test
675 °C no-steam sample 1	28,130	4.05	790	700 705
675 °C no-steam sample 2	24,600	3.54		560 620
675 °C w/steam sample 1	23,140	3.33	630	710
675 °C w/steam sample 2	24,140	3.47		450 460
870 °C no-steam sample 1	14,670	2.11	220	290
870 °C no-steam sample 2	11,280	1.62		350

* Concentrations calculated using sample gas volumes at meter conditions. Values in volumetric percent assume that the sample gas has a molecular weight of ~28. Tests were performed in the order shown.

Trace analysis general observation is that ammonia concentrations appear to be lower at 870C than at 675C gasification temperatures. The nitrogen oxide concentrations were not measured, so it is not certain if the higher operating temperature would benefit NO_x emissions. At 675 °C, the ammonia concentrations ranged from 3.5 to 4.0% without steam, and from 3.3 to 3.5% with steam. These results suggest that the addition of steam did not *substantially* affect ammonia levels at this temperature. Theoretically, the maximum ammonia evolution rate is around 4%.

The data suggest a general decline in hydrogen sulfide concentrations as testing progressed. After completing all the sampling from litter gasification, a 200 ppm H_2S stream from a compressed gas cylinder was passed through the sampling system downstream from the 450 °C particulate filter. Two identical H_2S readings of 190 ppm were obtained. While this result is encouraging, other experimentation and sampling experience during the development of the technique indicate that particulate collected in the sample line filter may significantly impact trace contaminant quantification. This is especially true if there is a high limestone particulate loading at the sample line filter. In most cases where there is a high loading of limestone dust collected in the sample line filter, the trace contaminant readings, especially hydrogen sulfide, tend to decrease over time. This greatly complicates interpretation of the hydrogen sulfide data.

Table 16 Gas Analysis Results for the BECON Air Blown BFB Gasification Tests, 800 kWth

	No Steam	No Steam	No Steam	Steam	No Steam
BECON Test #	1	2	3	4	5
Gas_n	CORN 675°C	Litter 675°C	Litter 675°C	Litter 675°C	Litter 870°C
O2	0.0%	0.0%	0.0%	0.0%	0.0%
CO	14.4%	7.7%	8.0%	6.9%	7.1%
CO_2	16.8%	19.9%	19.5%	19.9%	18.4%
CH_4	3.7%	2.2%	2.1%	2.0%	2.4%
H_2	6.4%	8.8%	8.0%	7.3%	5.3%
H_2O (ref)					
N_2	52.6%	55.5%	55.9%	57.2%	61.4%
C_2H_6	0.3%	0.3%	0.2%	0.2%	0.0%
C_3H_8	0.1%	0.0%	0.0%	0.0%	0.1%
C_2H_4	1.7%	1.0%	0.8%	0.8%	1.2%
MW (clean gas)	27.4	27.3	27.2	27.4	28.1
LHV (MJ/Nm^3)	**4.83**	**3.27**	**3.11**	**2.85**	**3.01**
Btu/scf	**130**	**88**	**83**	**77**	**81**

Milestone E: Build the Integrated Pilot Gasification and Cleanup System

The overall goal of this project was to build a successful gasification system for poultry litter that is reliable, produces clean gas and would be affordable for the on-farm or farm-scale application. One important consideration as began the design was that the produced gas heating value for gasified poultry litter in the air blown bubbling fluidized bed was much lower than is desired, especially at the larger scale. We took note of the bench scale fluidized bed experiments that suggested improved heating value could come from gasification at higher temperatures with lower equivalence ratios. This meant that the insulation design was very important. Secondly, any indirect heat addition that could be achieved through waste heat recuperation would also improve gas heating value. It was also important to have a high reliability for the gasifier, and so it was important to have a way to remove bed media during operation so that it could be cleaned and recycled back into the gasifier. The following design goals are featured:

- Start-up using LPG fuel with reliable Eclipse TJ025 vortex combustion burner.
- Heat recuperation from producer gas cooling at peak temperature (after the reformer)
- Layered refractory design: insulating fire brick, lined with dense refractory liner
- Flow distributor and vessel design that enables sampling of sand during operation
- Use of moving bed granular filter before 95% open area monolithic reforming catalyst.

<u>Process Flow Sheet</u>

Figure 16 presents a process flow sheet. Starting at the roots blower where air is compressed to about 0.2 atm through the roots blower and delivered to the system. On startup, air is delivered to the Eclipse TJ025 burner to provide startup heat. Air valve AV-1 and AV-2 are in their normal positions. A heat recuperative loop provides an efficiency boost after start-up by switching AV-2 open then closing AV-1. The temperature of the start-up gas from the Eclipse burner is controlled to 815C (max) to prevent overheating the stainless steel flow distributor manifold inside the fluidized bed reactor. Biomass is fed through the rotary air lock into a pressurized metering bin (~3 psig). The metering bin is purged with auxiliary air to prevent producer gas back flow when the air lock turns. This air purge constitutes about 15% of the air supply to the gasifier. Improvements to the air lock can reduce the minimum required purge, but the metering bin purge is essential to prevent fires in the metering bin. The metering bin regulates biomass feed into a constant speed injection screw that delivers biomass into the fluidized bed.

The reactor is filled with mullite sand (CE Minerals, Mulcoa-60) with an average particle size of ~0.71 mm, so the media will be fluidized at about 250C with 100 Nm^3/hr (~60 scfm) air. Alternatively, one could use olivine media with poultry litter, but silica sand is not recommended. Care must be taken when starting the gasifier from cold start until fluidization occurs. After the gasifier reaches about 400C using the Eclipse LPG burner, then biomass is fed in minimal amounts for combustion mode operation (excess air, equivalence ratio ER>2) until the desired reactor operating temperature is reached, preferably less than 875C.

Combustion gases and/or fuel gases are formed by reacting biomass with air inside the hot dense phase of the bubbling fluidized bed (BFB) reactor. Once the media inside the gasifier reaches 550C, the biomass combustion reactions are self sustaining and smoke is minimized. Exiting the gasifier, combustion or gasification gases will pass to the cyclone, then moving bed filter, tar reformer, heat recuperator, producer gas coolers then a final safety filter before delivery to the fuel gas application modules or flare. In startup mode, the moving bed filter is bypassed (dump line not shown) until the fluidized bed reactor reaches at least 550C, at this point the LPG burner can be shut off after which final heating of the BFB reactor can be supplied by biomass combustion. The Eclipse LPG burner should be off before the MBGF can be brought on-line.

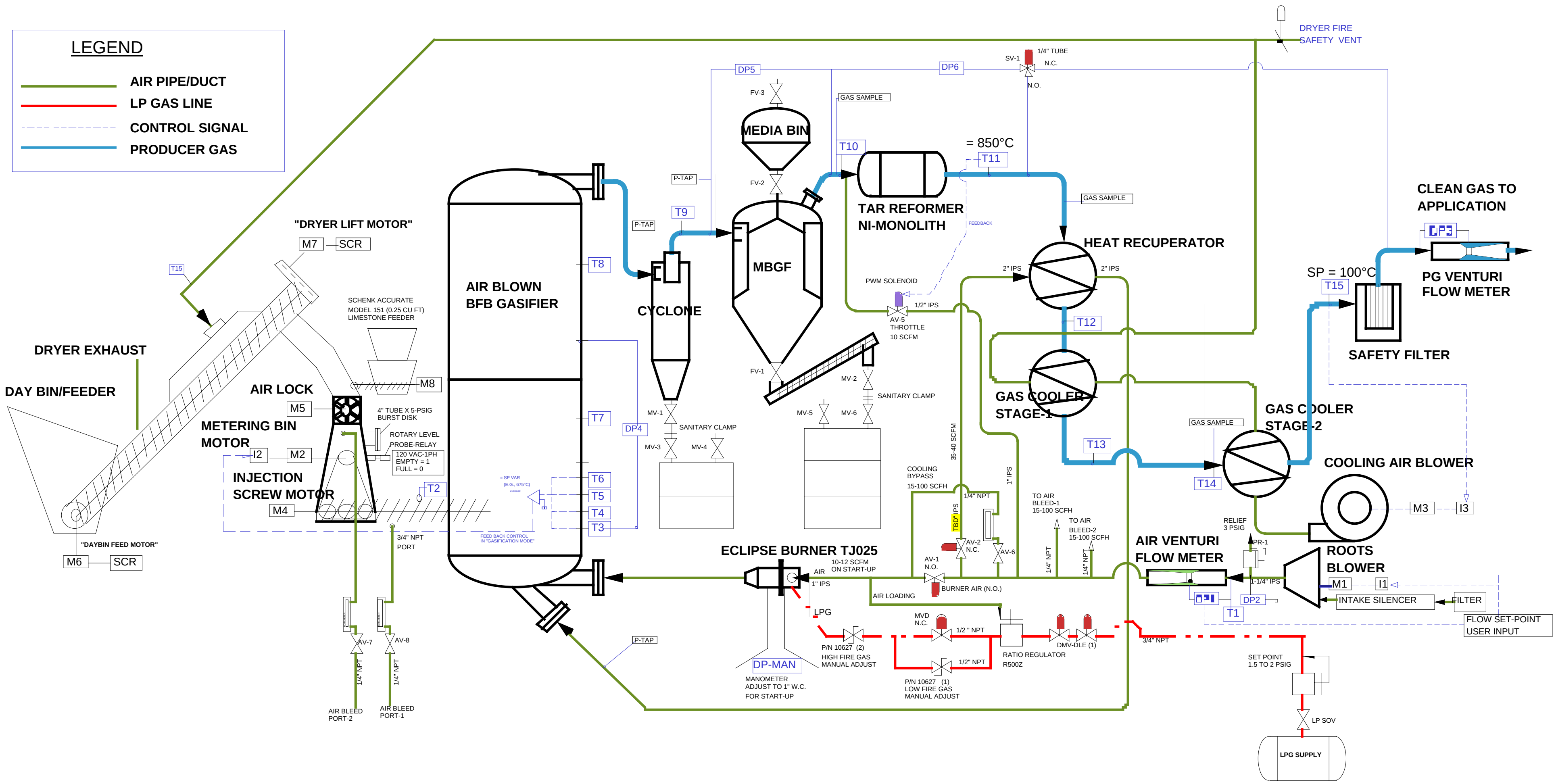


Figure 15 On-Farm Poultry Litter to Energy Gasification System, Simplified P&ID and Flow Sheet

The BFB reactor is operated in combustion mode until the MBGF achieves a suitable operating temperature, preferably an exit temperature >550C. Transition to gasification mode (ER = ~0.25) occurs by adjusting the air fuel ratio to a predetermined set-point for the given operating temperature. Afterward automatic control maintains the air flow rate to the gasifier constant while adjusting biomass feed rate to maintain the temperature set point.

In the future, we will modify the air distribution setup to improve independent operation of the gasifier. We will move the gasification air flow meter to just before the tee-in for the recuperator. Then the purge air and reformer air lines will be upstream of the gasification air flow meter and these lines will have separate flow measurement and control as required. This configuration will allow better automatic control of the gasification air independent of the purge air demand and variable reformer air requirements.

A large fraction of the char/ash particulate matter is removed from the produced gases with the hot gas cyclone. A future modification will eliminate the hot gas cyclone if the moving bed filter has automatic media cleaning and recycling. The moving bed granular filter (MBGF) removes finer particulate matter before delivery to the catalytic reformer.

The tar reformer is made of a 10" SCH 10 pipe section with 10" diameter catalyst monoliths installed inside for a total reformer length of 12". The catalyst is supplied by Sud-Chemie/ProtoTech and is composed of potassium promoted nickel catalyst wash coated on to a standard fecralloy honeycomb monolith with 95% open area. The reformer uses air addition to boost operating temperature (if required) and to burn-off any coke or soot that may build up on the inlet interface of the catalyst monolith.

The reformer would normally be bypassed until the MBGF reaches a suitable operating temperature to encounter producer gas. Preferably, the MBGF exit temperature is >550C and the BFB reactor is transitioned to gasification mode before the reformer is brought on-line. Once the reformer is brought on-line, then the recuperative heat exchanger can be brought online for an efficiency boost. The recuperator is especially useful to preserve gas quality when the MBGF exit temperature is below the desired reformer operating temperature. The recuperator can be configured to preheat reformer air as well as gasification air.

Use of the heat recuperator can add 5 efficiency points to the nominal gasifier efficiency. For example, suppose the pilot biomass gasifier is generating 100 Nm^3/hr of producer gas with a heating value of 5 MJ/Nm^3 at a nominal efficiency of 70%. This means that the fuel gas heat rate is 139 kWth (~474,000 Btu/hr), the biomass federate is ~ 198 kWth and the energy loss on gasification is ~59 kWth. If the producer gas contains 50% nitrogen, this means that the gasification air requirement is ~63 Nm^3/hr (81.5 kg/hr). Suppose the exit temperature of the reformer is 800C and the supply air temperature is 50C (after the roots blower), then by producer gas cooling from 800 to 475C, then ~13.9 kWth heat can be recovered from the producer gas to raise the gasification feed air temperature to 633C. (The heat recuperator is in a counter flow configuration so that the heated air temperature can exceed the producer gas outlet temperature). Even if ~20% of the recovered heat was lost on the way to the gasifier inlet, the net result is a ~5.5% fuel savings or a 4.4 point boost in efficiency! This efficiency boost is very important for poultry litter gasification because the low quality fuel produces a low quality gas. *Indirect heat addition by heat recuperation is one of our approaches to improve poultry litter fuel gas quality!*

Insulation Details

Another aspect of our approach to achieve higher quality fuel gas from poultry litter is attention to detail in the insulation design of the BFB reactor. Heat loss from the BFB reactor will increase the equivalence ratio (relative air/fuel ratio) required for gasification at a given temperature. The ISU lab-scale data shows that lower equivalence ratios will increase tar production, but there was also the indication is that lower equivalence ratios will improve fuel gas heating value. Quality insulation design is also very important for the small scale system since the relative amount of heat loss is significant compared to the internal heat generated.

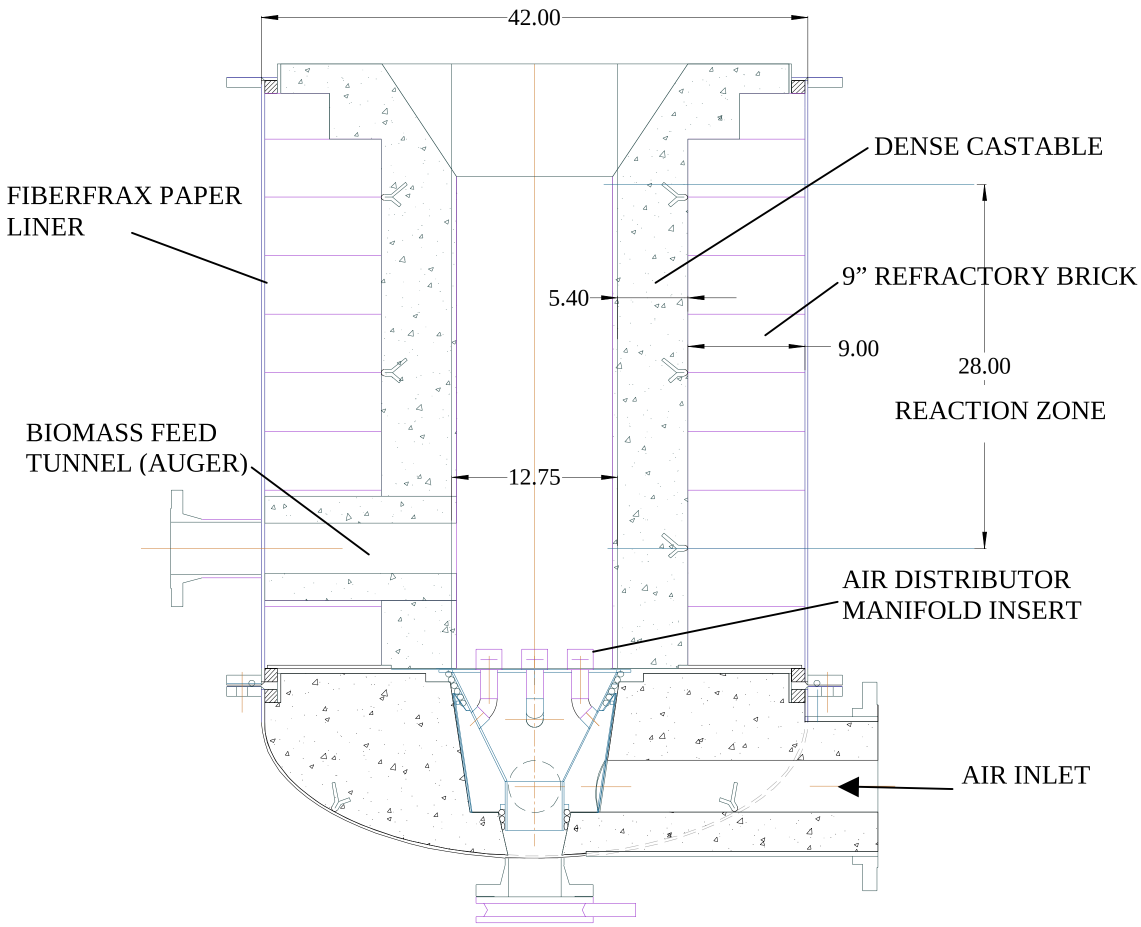


Figure 16 Lower section view of CPC's pilot gasification vessel. The insulation design features a Fiberfrax paper liner backing a 9-inch high performance refractory brick layer, plus 5.4-inch casting erosion resistant

Flow Distributor Detail

Finally, the last key feature of the poultry litter gasification system is the ability to perform media maintenance—meaning media removal, cleaning and recycling. The conical insert we designed for this purpose can be seen in Figure 17. The conical manifold enables air to be distributed to the bubble cap nozzles with a large throat opening for sand removal, even if substantial tramp material or clinkers had formed inside the reaction vessel. The insert is sealed against the refractory with a liner of Fiberfrax 550 paper plus high temperature rope seals. A 550C rated slide gate valve was purchased from DeZurik to allow brief sand removal while at operating temperatures. Flow distributor nozzles are drilled pipe caps, a design that was contributed by Jerod Smeenk (ISU).

The Integrated Pilot Gasification and Cleanup System for Poultry Litter

The integrated system was assembled in December of 2003. The following pictures document completion of the final gasification and cleanup system assembly.

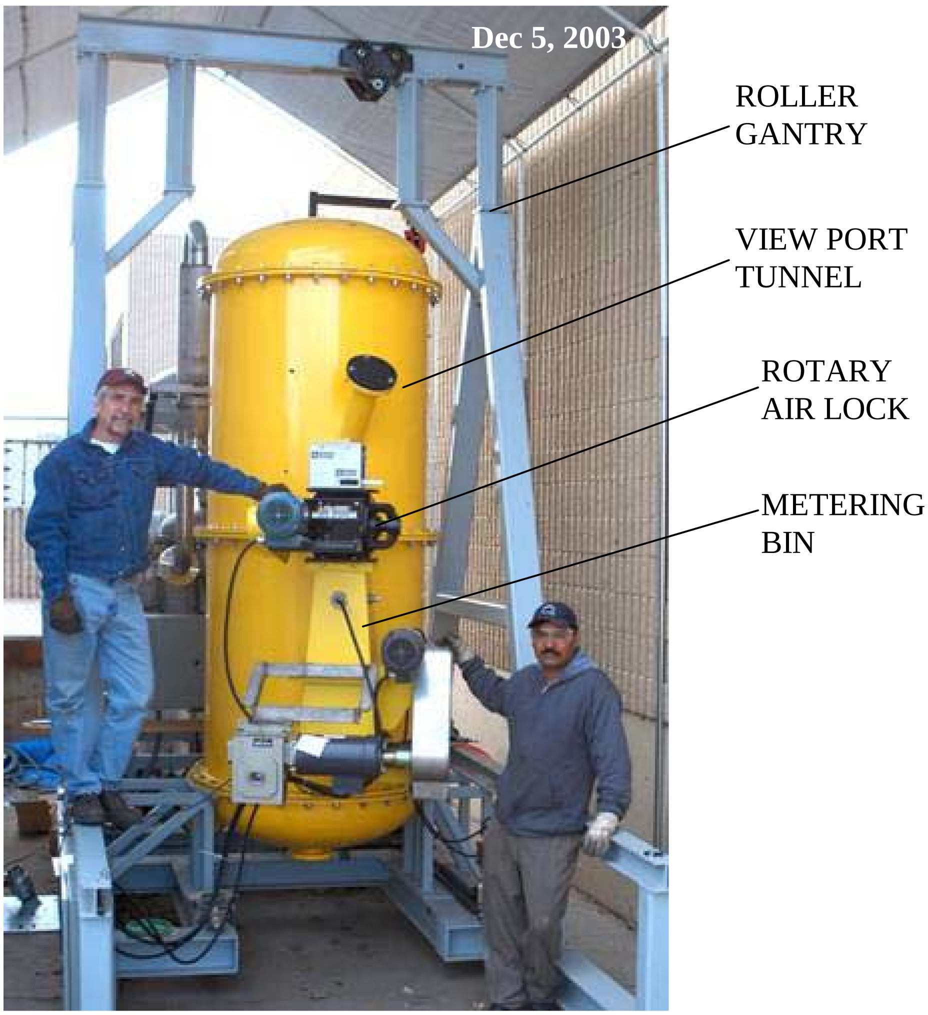


Figure 17 Front-View of BFB Reactor showing the air lock, metering bin and view port tunnel. The view port was later modified to include and air lock hopper for adding media.

Figure 18 Backside-View of Integrated System showing the MBGF (before insulation), cyclone, and gas coolers. Reformer and waste heat recuperator (not shown) sit in the space behind the vertical cooler.

Milestone F: Testing the Integrated System/ Operate Commercial Burners

The system was started up in January 2004. We worked through various start-up issues including control and electrical system debugging. We operated the system mainly in combustion mode though February as we were learning about gasifier startup and how to avoid large temperature gradients in cold start condition. Once fluidization is achieved at about 250C, then warm up to operating temperature is quite straightforward.

By the end of February we were able to bring the moving bed granular filter on-line. We experimented with media cleaning and designed simple barrel tumbler with a shop vacuum cleaner for final media cleaning. The granular media we purchased from the local aggregate company was called ¼" squeegee, which is basically a crushed and washed aggregate with a particle size in the range $^{1}/_{16}$ to ¼". While excellent in particle size, the media did have fines and dust that required cleaning before use. We found that the simplest method of cleaning the media is to use a vibrating screen. We did not take any quantitative particulate measurements while operating in combustion mode, but we did note that there was no detectible opacity in our stack gases after filtration by the MBGF if the reactor was operated above 550C.

By March it became clear that the original design for the air distributor manifold insert had sealing problems that affected the fluidization quality. The old manifold insert design used a flat flange to make a seal against the refractory using high temperature rope seals. The flat disk became warped due to radial temperature gradients. We redesigned the insert to use a conical seat seal, and this solution proved to be much more robust. We are careful to keep the startup combustion gases from the Eclipse burner to a temperature less than 815C to protect the stainless steel components. Once the gasifier is operating above 550C, then the Eclipse burner is shut off. We had no problems with air distribution even when operating the gasifier as high as 875C.

We operated the gasifier on corn stover in March and meet the milestones of a phase-I SBIR with applications in crop drying. The main lesson learned was that the corn stover had to be milled dry to less than ¾" to avoid feeder jamming problems and bridging of the fuel above the airlock. Start-up times were longer than the normal workday. Preferably the system is operated the day before to reduce the warm-up time required before testing on the subsequent day. In the field, the system would take about a day to warm-up and then would be operated continuously for six weeks to several months at a time.

Table 17 Corn Stover Gasification Test Data 4/14/04

Corn Stover Data	4/14/2004	NOVA Gas Analyzer	
tar sample #	**1502**	Gas_n	Mol %
T_gasifier (ave)	748	O_2	0.30%
T_Filter Inlet (T9)	475	CO	15.4%
T_Filter Exit (T10)	350	CO_2	19.60%
T_Reformer Exit (T11)	off-line	CH_4	5.80%
Reformer Average (T10,T11)	n/a	H_2	5.6%
LHV (MJ/Nm^3)	**4.63**	H_2O (ref)	0
Btu/scf	**124**	Balance N_2	53.30%
tars (mg/Nm^3)	**9,198**	Clean Gas MW	29.03

Most of our shakedown testing was performed using sawdust as a surrogate fuel. The volumetric feed rates for sawdust are about 50% of poultry litter at the same gasification temperature and thermal capacity.

The reformer was brought on-line in April 2004 using producer gas from sawdust fuel. We were able to add air to achieve reformer exit temperatures as high as 850C, but the filter exit (reformer inlet) temperatures were cooler than we would desire (usually 550 to 600C). We did not acquire any tar measurements for reformer exit temperatures above 750C.

One of the main issues we faced was the need for better thermal integration and sufficient warm-up time to achieve maximum filter exit temperatures. The highest filter exit temperature we achieved was ~570C. At first we were loosing as much as 150 to 200C across the filter, but after approaching closer to steady state by operating on consecutive days and by adding more insulation, this heat loss was reduced to about 100C. In the future, the hot gas filter will have automatic cleaning and media recycling, which will help reduce filter heat loss. At the present time the media reservoir was not insulated and received room temperature media. Therefore, all media must eventually be heated to the filter operating temperature. The media movement is slow, which minimizes the impact of heating cold media. However, media is removed with some residual heat, so if this could be cleaned and recycled while retaining some heat, then the media storage reservoir could be insulated and filter exit temperatures would be improved. Preferably we would like to have the MBGF (filter) exit temperature as high as 700 to minimize the amount of auxiliary air required to achieve reforming temperatures.

Table 18 Tar Sampling After the Reformer, Sawdust Fuel. Estimated 80 to 90% conversion of tars

Sawdust Data	4/21/2004	4/27/2004	5/11/2004
sample #	**1505**	**1503**	**1512**
T_gasifier (ave)	836	735	850
T_Filter Inlet (T9)	648	616	672
T_Filter Exit (T10)	506	407	499
T_Reformer Exit (T11)	647	755	456
Reformer Average (T10,T11)	576	581	478
tars (mg/Nm^3)	**3,015**	**949**	**909**
particulates (>0.7um)	179	395	277
fines (<0.7 um) (mg/Nm^3)	76	54	213

The results presented in Table 18 are a significant landmark! These are the first results of tar reforming after the moving bed granular filter in an integrated pilot-scale fluidized bed gasifier. The achievement of ~0.9 to 0.95 g/Nm^3 tars from a fluidized bed gasification system is remarkable. Indeed, our target tar concentration requires at least another 90% conversion. Ideally we would like to reduce tars to 30 mg to 50 mg/Nm^3. More work is needed on the gas cleanup system for the fluidized bed gasifier before pre-commercial deployment can occur. By April 2004, there was not sufficient time or money available to improve upon these results.

It is expected that the raw gas tar concentration from sawdust gasification in the BFB reactor is about 12 g/Nm^3 based on literature and operating experience—for example raw gas tars are greater than ~10 g/Nm^3 and less than ~15 g/Nm^3. Therefore we conclude that at least 90% tar conversion was achieved with the catalytic reformer, the exception being sample 1505, which may be as low as 75% conversion. To achieve tar concentrations less than 50 mg/Nm^3, we will need to achieve at least 99.5% conversion. At this point we believe the next logical step would be to add a partial oxidation stage after the gasifier to crack tars in the raw gas before encountering the moving bed granular filter. The indication is that the tar reformer needs to be at least twice as large, and the reformer certainly needs to be operated at higher temperatures, or higher filter exit temperatures! Replacing the cyclone with a char partial oxidation stage before the filter is one approach to improving thermal integration and tar destruction.

Tar measurements were taken during the May 7, 2004 tests on poultry litter. Tar conversions were determined to be 80% and 90% for two different samples. The reformer temperatures were quite low (<650). The raw gas tar concentration was much higher than for sawdust fuel at ~42 g/Nm^3 tar, but the gasifier was operating with lower equivalence ratios than normal and we were also using the heat recuperator.

Table 19 Tar Samples from Poultry Litter Producer Gas (5/7/2004)

Poultry Litter Data	5/7/2004	5/7/2004	5/7/2004
Tar sample #	**1508**	**1507**	**1506**
T_gasifier (ave) deg C	710	745	750
T_Filter Inlet (T9)	660	675	677
T_Filter Exit (T10)	558	566	570
T_Reformer Exit (T11)	NO REFORMER	614	586
Reformer Average (T10,T11) C	N/A	**570 C**	**578 C**
tars (mg/Nm^3)	41,787	8,511	4,595
particulates (>0.7um)	1,365	523	534
fines (<0.7 um) (mg/Nm3)	950	987	1,528
tar conversion	n/a	80%	89%

We observed that the heating value of the litter gas improved after the reformer. The average heating value of the gas sampled before the reformer was 3.2 MJ/Nm^3 (86 Btu/scf), whereas after the reformer the average heating value of the poultry litter fuel gas averages to 5.25 MJ/Nm^3 (141 Btu/scf). We observed a periodic oscillation of the methane number during our reformer tests with poultry litter gas. The pressure drop across the reformer increased to 3 to 4 inch w.c. during operation, but this effect was quickly mitigated by adding air. The pressure drop across the reformer returned to 0.7" w.c after increasing air for a short period.

Table 20 Gas Quality Measurements for Gasified Poultry Litter, Corresponding to tar samples

Poultry Litter	5/7/2004	5/7/2004	5/7/2004
Sample Ref#	**1508**	**1506**	**1507**
Gas_n	NO REFORMER	REFORMER	REFORMER
O2	-0.40%	-0.10%	-0.10%
CO	10.4%	11.5%	12.6%
CO2	22.20%	18.76%	19.80%
CH4	2.20%	4.17%	9.00%
H2	10.2%	11.5%	13.8%
H2O (ref)	**0**	**0**	**0**
N2	55.40%	54.17%	44.90%
Clean Gas MW	**28.66**	**27.54**	**26.53**
LHV (MJ/Nm3)	**3.20**	**4.19**	**6.31**
Btu/scf	**86**	**120**	**169**

Air addition to the reformer proved to be successful at maintaining a low pressure drop across the monolithic reformer. The assumption is that coke or soot would build up on the inlet interface of the monolith and contribute to reformer pressure rise. This soot would be subsequently burned off as we increased the reformer air flow rate. We have visually inspected the reformer catalyst and found soot at the inlet interface and pure carbon dust in tubes after the reformer. We also observed "hot spotting". Some portions of the monolith inlet interface had clear channels while others were coated with soot. This evidence suggests a need to improve mixing (air and producer gas) to give uniform control of carbon buildup.

We operated three 30,000 Btu/hr radiant tube burners using gasified poultry litter gas on May 11, 2004. These RTBs are used commercially for poultry house heating and also for brooding. We operated an internal combustion engine generator system on the poultry litter fuel gas on May 12, 2004. The poultry litter fuel gas had even higher concentrations of tars than the woodgas, so the engine was not operated very long or at a very high power level. We did load the engine generator to about 10 kWe using poultry litter produced gas. On May 11, 2004, we operated both the radiant tube burners and the engine on produced gas using sawdust fuel. We loaded the generator to about 21 kWe, while sustaining flare operating at the same time!

<u>Task-5: Demonstrate Integrated System Operating On Poultry Litter</u>

<u>Milestone G: Field Demonstration</u>

CPC held an on-site demonstration at its Littleton Colorado facility on Wednesday, May 12, 2004. The University of Arkansas site had reportable avian diseases and was under quarantine after April 2004. Therefore, we held our on-site demonstration at Community Power Corporation. Representatives from the poultry industry were invited and several attended this

Figure 19 Demonstration Day (May 12, 2004) L-R: Jason Thibedeux (CPC), John Reardon (CPC), John Askegaard (Tyson Foods, Inc.) and Frank Jones (University of Arkansas).

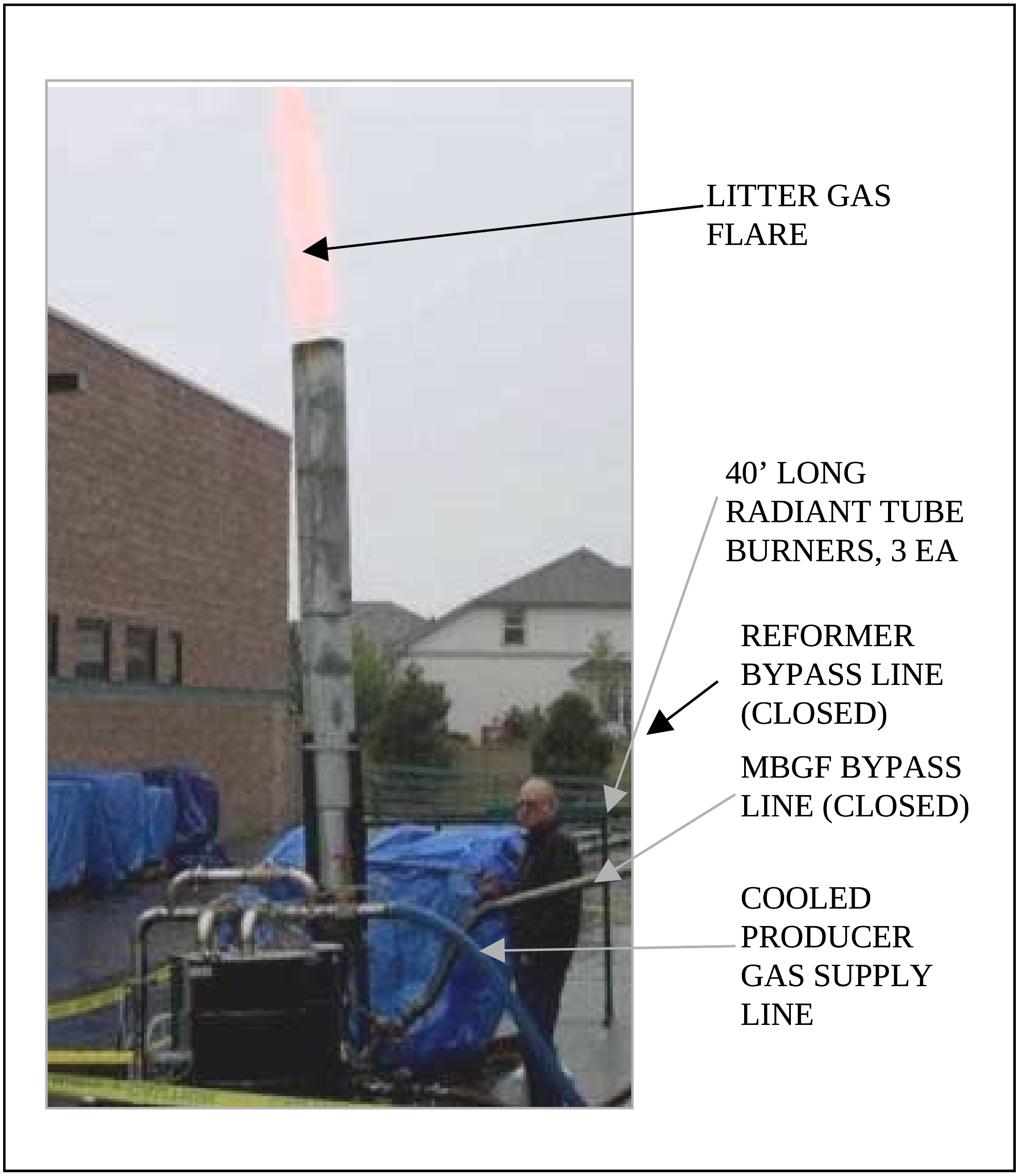


Figure 20 Flare operating on ~130 kW_{th} producer gas from poultry litter. May 12, 2004.

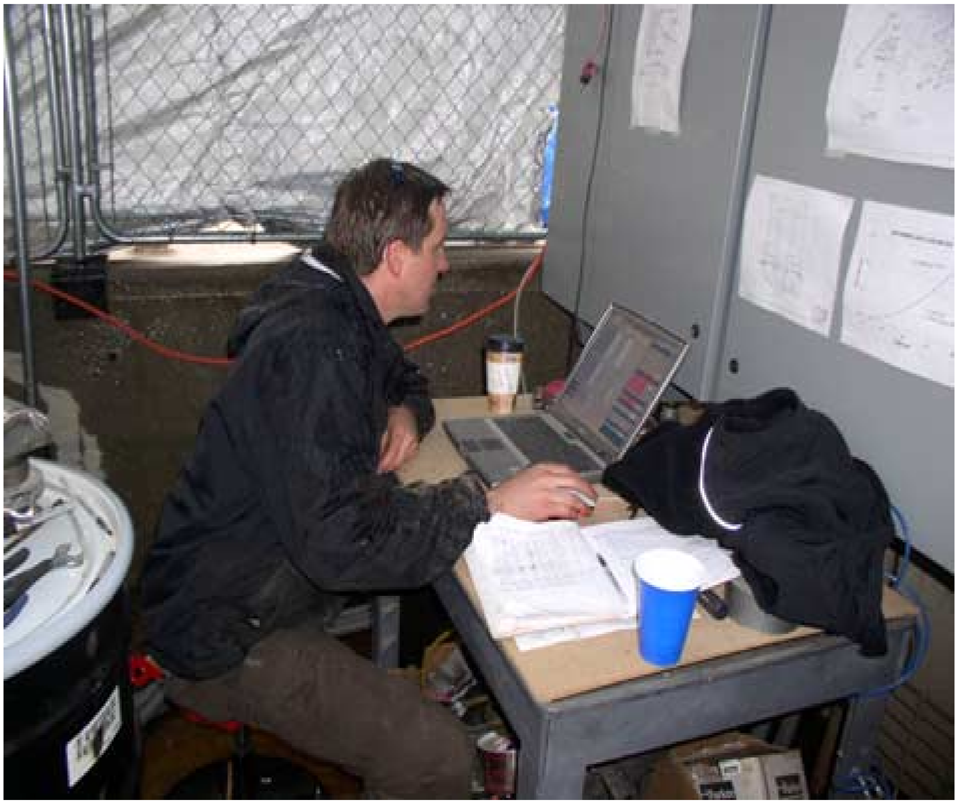


Figure 21 Reardon at Litter Gasifier Control Station (May 12, 2004)

Task-6: Interact with the Industry Advisory Panel

No milestone was attached to this task. Jim Wimberly assembled an industry advisory panel (IAP) in Northwest Arkansas. Mr. Reardon and Mr. Lilley met with the IAP early in the Phase II project. Their input guided us in how we thought about an on-farm litter to energy system. Their preference would be a system that produces a fuel that can be readily stored, such as a liquid fuel. Preferably, they would like a single system that could serve the needs of several farms, converting the participating farmer's litter to liquid fuels. We were advised to minimize the operating labor requirements for the farmer, and to integrate with the farms energy distribution system in a seamless way. Therefore, it was important to be able to develop a highly reliable system that generated clean gas for use in commercial furnaces and radiant brooders.

Task-7: Prepare System Documentation Package

Milestone H: Complete Documentation Package

The original engineering for the gasifier and feeder was provided by T.R. Miles Technical Consultants. Shop drawings were prepared by TRM for the original gasifier concept. The poultry litter gasification system requires further development to improve the gas cleaning for more extensive tar conversion.

We kept the basic gasifier shell and air lock metering bin from the TR Miles design, but made modifications to the bottom section to accommodate two air entry ports, one for startup combustion air and the second for heat recuperator air. We also made modifications to the shell assembly to accommodate the air distribution manifold and to accommodate our improved insulation design. We modified the TR Miles insulation design by incorporated a high performance refractory brick liner to backup the dense refractory pour.

Randy Keen (CPC) documented the gasifier shell modifications and also created shop drawings for the heat exchangers used on this system.

John Reardon created P&ID drawings for the system and also documented the insulation design as well as the revised air distribution manifold.

John McCall documented the system assembly with a solid model.

Dusty Duncan documented the power distribution and control system.

Task-8: Prepare Business Plan

Milestone I: Complete Business Plan

On-farm Vs Central Facility

The fundamental question is "does the industry see a need for an on-farm system, and if so, does it have a chance against a centralized facility?"

The consensus view of the Industry Advisory Group is that there is a need for on-farm systems, and that both options have advantages and disadvantages. The major advantage for central facilities is that they can consume large quantities of litter, and the technology currently exists. The major disadvantages are the bio-security issue, and the poor economics of wholesale generation and sale of electricity.

The primary advantage of the on-farm approach is that it virtually eliminates the bio-security issue, and it can compete with conventional energy prices at the retail level. The main disadvantage is that it is new, unproven technology, and its capital cost is high in small volumes.

There are 86,000 individual poultry houses in the United States; therefore, the potential equipment market is in excess of $3.75B.

System Characteristics

As mentioned earlier, the main need on a farm is for thermal energy. The high prices of natural gas/propane combined with the low price of electricity and the technical difficulty of generating electrical power begs for a thermal solution.

A thermal system of about 1.7 MMBTU/Hr would serve the needs of a typical four-house farm. Producer gas would be piped to individual houses and the thermal energy distributed via radiant tube heaters.

The net price, after incentives, for such a system is projected to be in the range of $175,000 and would serve at least four houses, or the typical average poultry farm.

Competition

Competition for the proposed on-farm system include: 1) retail propane and natural gas and 2) litter combustion systems.

The pricing strategy for the LIMCO model would neutralize the advantage of the propane/natural gas competitor.

The gasifier-based system would be superior to a combustion-based system primarily on the basis of emissions. It would be difficult to compete on price against a combustor even if each house had its own combustor. If regulators understood that an option existed that was environmentally superior to the combustor, it is conceivable that permits would not be extended to the combustor option.

Sales Options

Several options were considered for selling systems for on-farm application. These options included:

1. Direct sale of systems to farmers
2. Leasing systems to farmers
3. Selling systems to a litter management company

Based on feedback from the Industry Advisory Group options 1 and 2 have a low probability of success in the early years given three factors:

1. This is a new technology without benefit of a track record
2. For option 2, farmers will be averse to taking on a sizeable capital equipment expense, and will prefer to continue to pay high fuel prices
3. Many farmers will not be willing to spend more time, even if it is only a ½ hour per day to tend to the needs of the on-site system.

Therefore, Option 3, the Litter Management Company (LIMCO) is the preferred way to deploy systems on a large scale. There are numerous advantages of this concept:

1. The farmer will be able to dispose of his litter with no capital outlay, and pay an amount for energy equal to the current outlay.
2. The farmer will not have to tend to the system, the LIMCO will accomplish that goal.
3. The LIMCO can aggregate enough farms in a given location to be able to spread its fixed costs.
4. The LIMCO has the option to also manufacture the systems, thereby defraying the sales markup and handling charges of an intermediary.
5. The LIMCO can take maximum advantage of tax breaks, and incentives.
6. Poultry integrators are logical LIMCOs, since they already have a working relationship with the farmers, and make routine deliveries of birds and feed to them. Therefore, there

would be no incremental capital investment for transportation equipment, minimal increase in labor, and no incremental bio-security risk.

Market Drivers

It is apparent when discussing the situation with industry participants, whether it be farmers or integrators, the issue is not one of environment, but economics. A typical response is that, "I can always get rid of my litter. It's just a matter of how far I have to ship it, and how much it costs me."

Therefore, the most important market driver is cost, not regulation. In fact, most believe that the market will decide the issue, not regulation. Increased transportation costs will either be passed on to the consumer, or absorbed by the farmer/integrator. Some will probably exit the business while others may enter. The cost of shipping would represent a small increase in poultry prices, and would probably do little to stop the public's purchase of this food product.

Capital Cost Estimate

Scaling up from the pilot scale by a factor of about three with attendant savings in volume production savings will reduce unit equipment cost for the farm scale system.

Table 21 Retail Cost Estimates for Thermal-Only* Modular Litter to Energy System

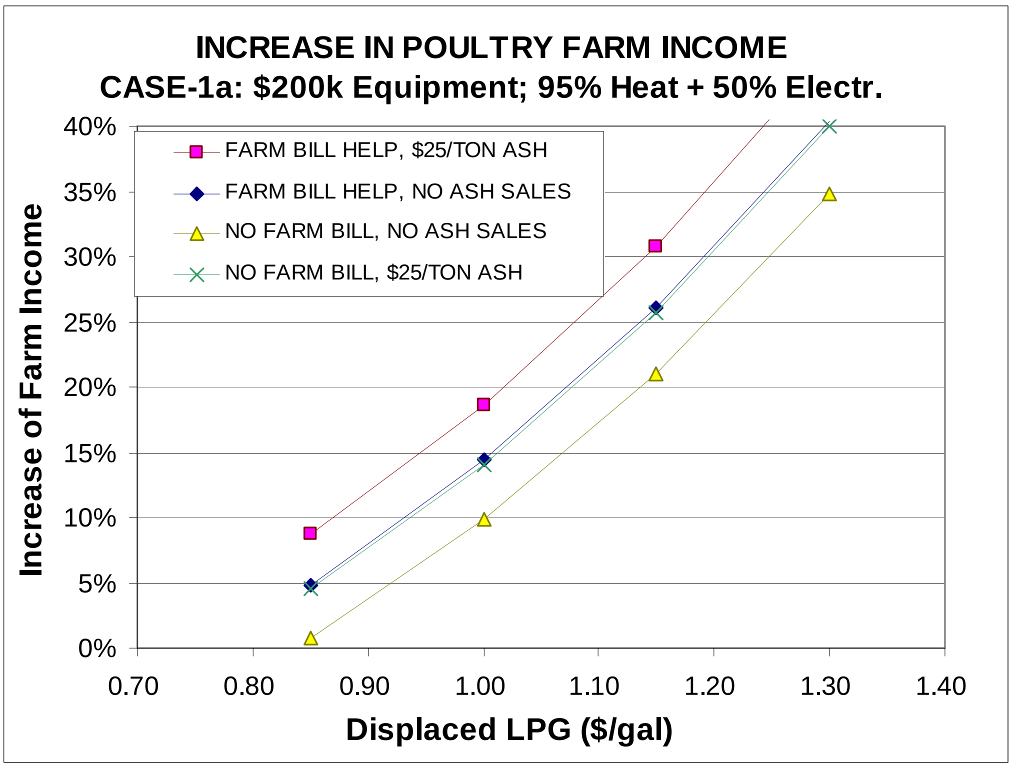
Rating (kWth)	180	495
Rating (MMBtu/hr)	0.6	1.7
Component	Pilot System	Farm Scale Cost**
Gasifier	20,000	29,358
Air Lock Metering Bin	10,000	18,348
Controls Hardware	12,000	12,000
Power Distribution	2500	4,587
Hot Cyclone/POX reactor	3,500	6,422
MBGF	33,990	49,893
media clean and recycle	3,500	6,422
roots blower	2,500	4,587
Reformer Vessel	2,000	3,670
Catalyst	1,200	2,202
Heat Recuperator	2,500	4,587
Gas Cooler-1	1,000	1,835
Gas Cooler-2	1,000	1,835
Eclipse Burner	1,250	2,294
LPG components	1,200	2,202
Air Distribution Piping	2,000	3,670
Duct work	1,000	1,835
miscellaneous	10,114	18,558
total	111,254	174,303
Assembly Labor	15,000	20,000
15% Margin	16,688.10	26,145.47
Retail Price	**$ 142,942**	**$ 220,449**
20% Farm Bill Discount	$ (28,588)	$ (44,090)
Price After Farm Bill	**$ 114,354**	**$ 176,359**
Equipment $/MMBTU	**$ 190,590**	**$ 103,740**

*If electricity is desired, assumes that we can retrofit existing backup generator

*Estimated cost of farm-scale system.

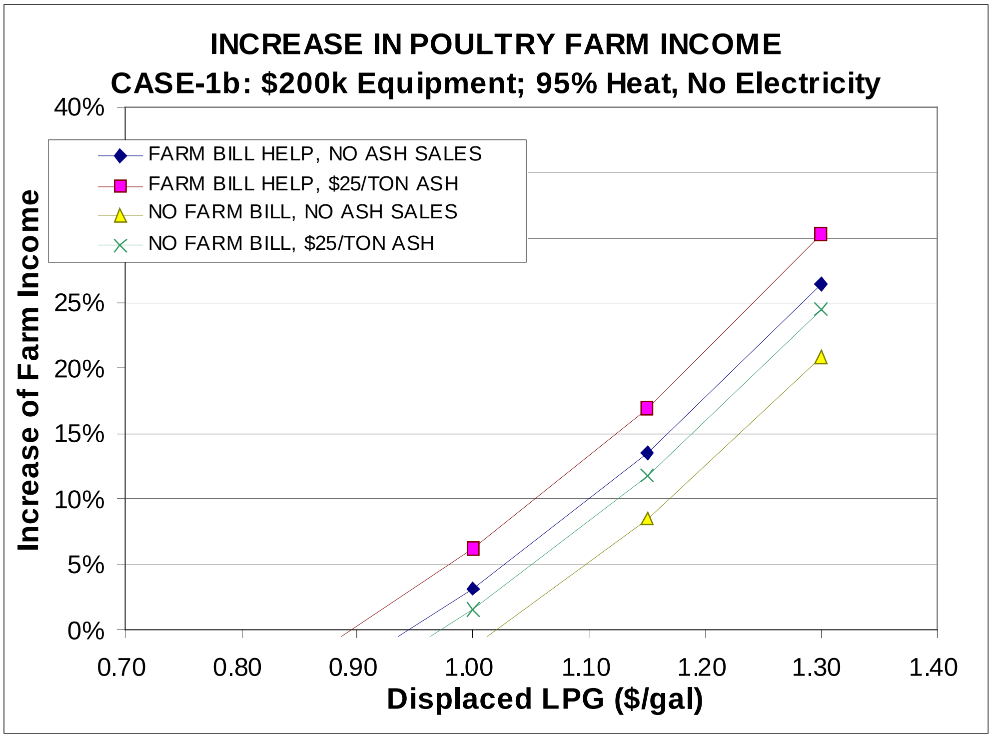
Potential Increase in Revenue

Using Economic analysis approach and spreadsheet equations from the Auburn University[28], we estimated the increase in revenue for the farmer relative the baseline income derived by the UA. This analysis evaluates farm income in the middle of the enterprise life cycle. The results indicate that, for example, if LPG costs 1.20/gal in the middle of the equipment life, then the farmer's income will be increased by 25% to 35% if he can displace 95% of his heating fuel need and 50% of his electricity.



The figure above assumes the farmer already owns the generator or the incremental costs are included in the $200k equipment cost.

[28] Gene Simpson, Auburn University Extension Services, Alabama



Financial Analysis

This section provides a discounted cash flow analysis of the following five different options.

1 Land Application of ½ of the litter + supply 95% of the heat

2 Supply 95% of the power and use the waste heat

3 Supply 95% of the heat

4 Supply 95% of the power

5 Supply 50% of the power and 95% of the heat

Assumptions used in the analysis:

1. 440 tons of litter is available
2. On-farm optional uses of litter are for power, heat, and land applied fertilizer.
3. Land applied litter is valued at $12.50 per ton.
4. Only 50% of the litter is able to be land applied due to saturation effects.
5. Unused litter is shipped off-farm at a cost of $10 per ton
6. Electricity assumptions

95% of annual utility electricity expense	$7,980.00
Electricity cost	$0.07 per kWh

kWh 114,000 kWh/yr

Litter conversion efficiency 18.9%

7. Heat assumptions

   LHV of litter 6,000 Btu/dry lb

   Gasifier efficiency 70%

   Propane LHV 84,500 Btu/gal

   95% of propane/yr 22,800 gal

   95% of annual heating cost $22,800 per year

8. Model assumptions

   Electricity Inflation Rate (%): 2.0%

   Heating Fuel Inflation Rate 2.0%

   Loan Down Payment (%): 85% (cash) 15% (finance)

   Interest Rate (%): 9%

   Loan Term (Years): 8

   Net Federal Tax Rate (%): 35%

9. Capital cost $220,000 (assumes farmer has generator already)
10. Farm bill assistance 20% of capital cost
11. O&M Costs $0.03 per kWhe + $0.01 per kWht
12. Project life 20 years
13. No ash sales

The results of the analysis are as follows:

Option	NPVof cash flows	Internal Rate of Return
Land Application ½ + 95% of the heat	$204,000	20%
Supply 95% power and use waste heat	$24,000	2%
Supply 95% of the heat	$165,000	16%
Supply 95% of the power	($39,000)	<0
Supply 50% of power and 95% of heat	$227,000	24%