Final Report:
Commercialization of Biomass Direct-fired Heating Systems
Cooperative Agreement # DE-FC48-97R810642

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Commercialization Ventures Program

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Executive Summary

There is a great need for lower-cost heating systems on broiler farms. Management options are also needed for surplus broiler litter generated on the farms, as well as surplus sawdust generated by many small-scale sawmills. A farm-scale bioenergy system using litter and/or sawdust to produce thermal energy could address all of these needs. Accordingly, there appears to be an attractive business opportunity for development and deployment of such a bioenergy system(s). In addition to reducing farmers' operating costs, such systems could displace fossil fuels with renewable biomass and, for litter-fired systems, help the poultry industry address concerns associated with current litter management practices in many areas of concentrated production.

However, the challenges of developing and deploying such farm-scale bioenergy systems are not to be underestimated. Numerous efforts and countless funds have been expended by many organizations and individuals in pursuit of such systems, but so far without commercial success. To be commercially viable, a furnace system must satisfy three fundamental criteria:

- Technically viable – The furnace system must be functional, reliable, and robust, and able to withstand operating conditions encountered on broiler farms.
- Economically feasible – The furnace system must be affordable by the consumer (i.e., the poultry grower) and represent a positive return on investment; supplemental financial assistance may be available from public and/or private sources to offset the cost of such on-farm bioenergy systems (assuming that the systems satisfy the other two criteria).
- User friendly – The furnace system must be readily usable by the broiler farm operator under farm conditions. In other words, the unit should require very little attention, management, or technical expertise, and must not interfere with broiler production efforts.

Four prototype farm-scale biomass-fired furnace systems were developed and tested since 1997 with funding support by the U.S. Department of Energy through its Commercialization Ventures Program. The four systems included a pellet-fired system developed by Pyro Industries, an unprocessed biomass-fired system designed by Larry Dobson with Northern Light R&D, and two unprocessed biomass-fired systems developed by External Power in conjunction with Wood-Mizer (based on Dobson's design). This report discusses the activities and results of these efforts…information that may be of interest to others pursuing such farm-scale energy systems.

For a variety of reasons, none of the efforts under this project were successful in terms of commercializing and marketing a biomass-fired furnace for heating poultry houses. In fact, with regard to the three commercialization criteria set forth above, none of the systems were able to satisfy the first criterion (technical feasibility). However, as noted in this report, considerable information was compiled and numerous lessons were learned that should be of benefit to others that are pursuing (or considering pursuit of) such systems.

While the concept of developing and deploying farm-scale bioenergy systems for heating poultry houses is extremely attractive – particularly so for litter-fired systems – commercialization of such systems remain elusive, and results of efforts to date indicate that the challenges might be insurmountable. Nonetheless, the potential benefits from deployment of these systems continue to attract attention and interest, and may warrant additional investment (from public and/or private sources). Such attention and interest has increased in recent years due to water quality concerns associated with traditional poultry litter management practices (i.e., land application).

The technical challenges facing farm-scale bioenergy systems are associated with several different components of the system, including fuel storage and handling, ash management and emissions controls, and the furnace itself. For each of these components, the technical challenges of using litter as fuel are considerably greater than for sawdust- or pellet-fired systems. However, a major benefit of a litter-fired system is that all of the phosphorus contained in the litter would be captured in the ash…an inorganic fertilizer material with significant market value that could be exported from the poultry farm, thereby addressing the farm's surplus phosphorus concerns.

The primary economic benefit of these systems would be the value of the displaced propane (the target displacement level is 85% of current usage). Litter-fired systems have an additional economic benefit…the value of the ash co-product. The economic analyses set forth in this report indicate that farm-scale bioenergy systems deployed for heating broiler houses would be feasible…***if*** the technical challenges can be overcome, the economic assumptions set forth herein are correct, and the prices paid by growers for propane continue to rise. Deployment costs could be reduced through funding support from various federal/state funding programs and/or by financial assistance from integrators, particularly for litter-fired systems. However, no amount of supplemental financial/economic assistance will ensure successful deployment if the furnace systems are not technically viable and user friendly.

Successful sales and marketing of farm-scale biomass furnace systems by the equipment manufacturer/vendor would also require in-depth knowledge of the poultry industry, development of financing options, establishment of an after-sales product support structure, and coordination with both growers and integrators. These efforts could be more effectively pursued on a regional basis, i.e., within specific areas of concentrated broiler production.

Pellet-fired furnace systems have significant technical advantages over sawdust- or litter-fired systems and could probably be developed and deployed relatively quickly. However, the economics of pellet-fired systems are dismal, primarily due to the high cost of pellet manufacturing. Development of less expensive pelletizing technologies—for both sawdust *and* litter pellets—could improve the economics and facilitate deployment of pellet-fired systems. Going one step further, a mobile pelletizing system could process the litter/sawdust at the farm or sawmill, eliminating the high cost of transporting the material to and from a distant processing facility.

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1. Introduction

1.1. Background

There are an estimated 130,000 broiler houses in the United States, mostly in the southeastern region. Fuel for space heating is the single greatest operating expense for broiler production facilities. Approximately seventy-five percent of producers use propane, primarily due to the farms' rural locations; most of the other facilities use natural gas.[1] Each facility produces litter, a mixture of manure and bedding material. In addition, most are near sources of sawdust, given the common geographic correlation of the forest products and poultry industries in the southeastern United States.[2] Increasingly, alternatives are needed for managing surplus poultry litter[3] and for managing surplus sawdust and other woody residues.[4]

Both litter and sawdust are forms of biomass and have significant energy content. As such, these materials could be used as fuels for energy systems on the broiler farms, thereby displacing at least some of the fossil fuels currently being consumed while also providing new management options for the surplus litter and/or the surplus sawdust. Such a scenario would constitute a win-win-win outcome:

- ***Economic benefits*** – reduced fuel expenses for poultry growers, and reduced potential liability associated with surplus litter/sawdust management.
- ***Environmental benefits*** – displacement of fossil fuels and avoidance of air/water quality concerns associated with traditional sawdust and litter management practices.
- ***Renewable energy production*** – use of renewable biomass fuels.

Commercial systems exist for large-scale conversion of litter/sawdust into thermal/electrical energy. However, no such systems have yet become commercially available specifically for broiler farms. Thus, there is a definitive need – *and a potential business opportunity* – for adaptation of existing large-scale bioenergy technologies for these relatively small-scale applications.

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[1] In rare instances growers use coal-fired or cordwood-fired furnaces, typically located within the house to take advantage of radiant heat as well as forced air from the system.

[2] It is estimated that at least 65% of the broiler facilities in the southeastern U.S. are within 20 miles of a source of sawdust, i.e., a primary or secondary wood products facility that generates some woody residues. This is particularly true for most poultry production areas with the Ozark Highlands Plateau region, an area covering northern Arkansas, southern Missouri, and northeastern Oklahoma, whose primary rural economies are forest products and animal agriculture.

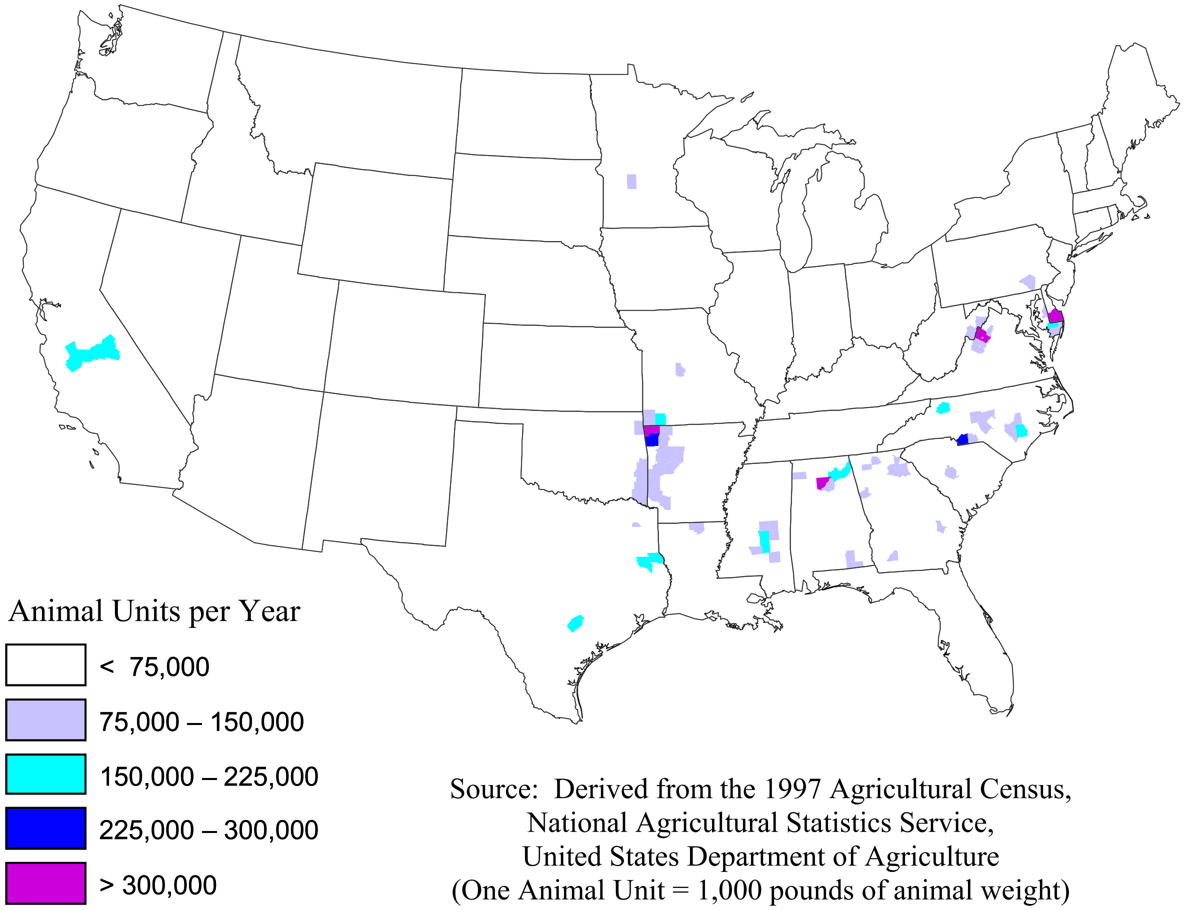
[3] Surplus litter is considered that portion of litter produced by broiler operations that should not or cannot be managed using traditional methods (i.e., application on agricultural lands on or near the broiler farm) due to concerns regarding potential nonpoint source water pollution – such concerns are increasingly associated with areas of concentrated poultry production.

[4] Surplus sawdust is considered that portion of the woody residue produced by primary/secondary forest products operations for which there is no feasible management option, primarily for economic reasons (e.g., small-scale, rural-based sawmills that cannot justify using the material for on-site energy generation).

1.2. Understanding the Opportunity

From an equipment manufacturer's perspective, the potential market for on-farm furnaces is significant: deploying bioenergy systems on 50% of the broiler farms in the southeastern United States would represent sales of about 50,000 units. In addition, these systems could be used for heating turkey houses and perhaps other animal production (e.g., hog barns) and rural facilities. The primary geographic locations of the potential markets for such furnaces are depicted in Figure 1, which shows poultry production in the continental United States. Plus, there would likely be other markets for these small-scale biomass heating systems such as other types of farm buildings, rural maintenance shops and fabrication facilities, and schools and other public facilities located near sources of surplus sawdust.[5]

Figure 1: Poultry production in the United States



Source: Derived from the 1997 Agricultural Census,
National Agricultural Statistics Service,
United States Department of Agriculture
(One Animal Unit = 1,000 pounds of animal weight)

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[5] Some such facilities in the OHP area are still being heated using cordwood-fired furnaces; automated furnace systems using locally available sawdust as fuel could substantially increase the reliability and operational efforts associated with these systems.

1.3. Understanding the Challenge

While the potential business opportunity for developing and deploying small-scale bioenergy systems designed specifically for broiler farms is considerable, the potential challenges of such an undertaking are not to be underestimated:

- ➢ The poultry industry is considered to be conservative and risk-averse, in large part because competition within the industry is keen, profit margins are thin, and potential liabilities associated with production system failures are large.[6]
- ➢ Broiler houses have high and variable heating requirements. For example, a typical 40-foot by 400-foot broiler house in the Ozark Highlands Plateau (OHP) region requires in-house temperatures greater than 90˚ F. during the first ten days after chicks are delivered to the farm, regardless of external temperatures and conditions…these conditions must be maintained within a building that has sidewalls consisting of plastic sheeting, with ventilation fans that come on intermittently that exhaust large volumes of conditioned air.
- ➢ The poultry industry has a high comfort level with existing gas-fired heating systems:
  - Broiler chicks are perceived to prefer existing radiant brooder heaters rather than forced-air heating systems (sometimes this is referred to as the "mothering effect").
  - Existing gas-fired heating units have proven convenience, reliability, & low cost.
  - Existing equipment suppliers are close to (and often inside) the poultry industry and are well-established.
- ➢ To be successful, any new system must accommodate existing broiler operations and:
  - Must be technically viable.
  - Must be economically feasible.
  - Must have acceptable "hassle factor" to users.

1.4. About this Project

The goal of this project was to commercialize existing and innovative biomass-fired furnace systems for heating poultry houses, which will improve the economics of poultry production, develop new markets for surplus woody residues and surplus poultry litter, and reduce consumption of fossil fuels. The objectives of this project were to:

- ➢ Scale up an existing prototype small-scale green sawdust-fueled heating system and adapt it for use in heating poultry houses.
- ➢ Adapt the same system to use poultry litter as fuel.

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[6] For example, an entire flock of 20,000 birds can be lost within one hour if in-house temperatures drop significantly during winter periods due to failure of the barn's heating system.

- Scale up an existing pellet-fired residential heating system and adapt it for use in heating poultry houses.
- Demonstrate and evaluate the technical and economic feasibility of the systems on a full-scale calibrated poultry house facility and other field sites.
- Work with the equipment manufacturer(s), the poultry industry, and other organizations to commercialize the technology.

Project activities focused on broiler farms, although, as noted in section 1.2, these same or slightly modified systems could also be used for heating turkey houses and for other rural heating applications. The primary geographic focus of this project was the Ozark Highlands Plateau, although the results would likely be applicable to other areas of concentrated production in the southeastern United States (refer to Figure 1).

1.5. Project Participants and Implementation History

Funding for project activities was provided by the U.S. Department of Energy (DOE), with a 1-to-1 match provided by the cooperative agreement recipients. The prime recipient was the Arkansas Energy Office (AEO, a unit within the Arkansas Department of Economic Development), although all of the funds were sub-granted by AEO to the Foundation for Organic Resources Management (FORM), a nonprofit organization based in Fayetteville, Arkansas. FORM served as the overall project coordinator and administrator and subcontracted to other entities as described below for product development and performance analyses.

The original partner responsible for product design, development, and commercialization was Pyro Industries (Pyro), a for-profit company based in Burlington, Washington. Pyro was a leader in the pellet-fired stove industry and as such had a proven and successful track record of developing and commercially deploying small-scale bioenergy systems worldwide. Pyro's tasks were two-fold: 1) adaptation and subsequent commercialization of its in-house residential-scale pellet-fired technology for the targeted poultry house furnace applications; and 2) adaptation and subsequent commercialization of an innovative green sawdust-fired furnace technology for the targeted poultry house furnace applications through technical assistance to Mr. Larry Dobson with Northern Light R&D, the original furnace designer who is located in Clinton, Washington (through a subagreement between Pyro and Northern Light).

The University of Arkansas (UA) was engaged to assist with on-site demonstration, testing, and performance analyses of the furnace systems. UA was particularly well suited to assist in these capacities given its location (in the heart of the poultry industry within the OHP), its substantial and multi-disciplinary technical and economic support to the region's poultry industry, and its Broiler Energy Research Facility. UA's Broiler Energy Research Facility is a 4-house broiler farm constructed in 1990 about ten miles west of the UA campus that serves as a typical full-scale 4-house contract broiler production operation, except that each of the four production houses is wired for monitoring of key energy parameters, enabling testing and demonstration of various energy-related technologies associated with broiler production facilities. As such, the facility had already accumulated substantial experience and baseline data regarding gas-fired broiler house heating systems prior to commencement of this project in January 1997 and served as an outstanding facility for assessing performance of units developed under this project.

In late 1999, Pyro Industries was purchased by Lennox Industries. Soon after, the new company determined that poultry house heating did not fit within its target product portfolio, and Lennox/Pyro withdrew from the project. Accordingly, mid-course corrections were required for continued pursuit of the project's goals, including: a) termination of efforts regarding development and testing of the prototype pellet-fired furnace system developed by Pyro and installed at the UA facility; b) direct coordination with Northern Light re development of the raw material furnace; and c) initiation of a search for a new for-profit project partner that had sufficient interest level, in-house product development resources, and proven bioenergy systems commercialization experience to pursue and complete the objectives of this project.

In May 2001, FORM, UA, and Northern Lights staff initiated discussions with External Power LLC,[7] a subsidiary of Wood-Mizer, the leading manufacturer of portable sawmills worldwide.[8] Together, External Power and Wood-Mizer (EP/WM) had determined that the furnace system designed by Dobson might be able to serve as the heat source for their Sterling engine system. In addition, EP/WM began to consider developing and commercializing the thermal systems being pursued through this project.

In June 2001, EP/WM borrowed the first-generation unit designed by Dobson (which was named "Chick" by project participants) and relocated it to WM's research and development facility in Madisonville, Kentucky, for in-depth performance analyses. By September 2001, EP/WM had, using other resources, constructed and tested a second-generation unit (referred to as "Woody1"). EP/WM concluded that the system displayed sufficient potential to warrant further investment in product development, both for its Sterling engine application and for the poultry house heating

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[7] External Power (EP) was established to develop and commercialize small bioenergy systems, with a primary focus on Sterling engine technologies; when EP met with FORM in May 2001 re this project the company's efforts were being supported by DOE through its Small Modular Biopower program.

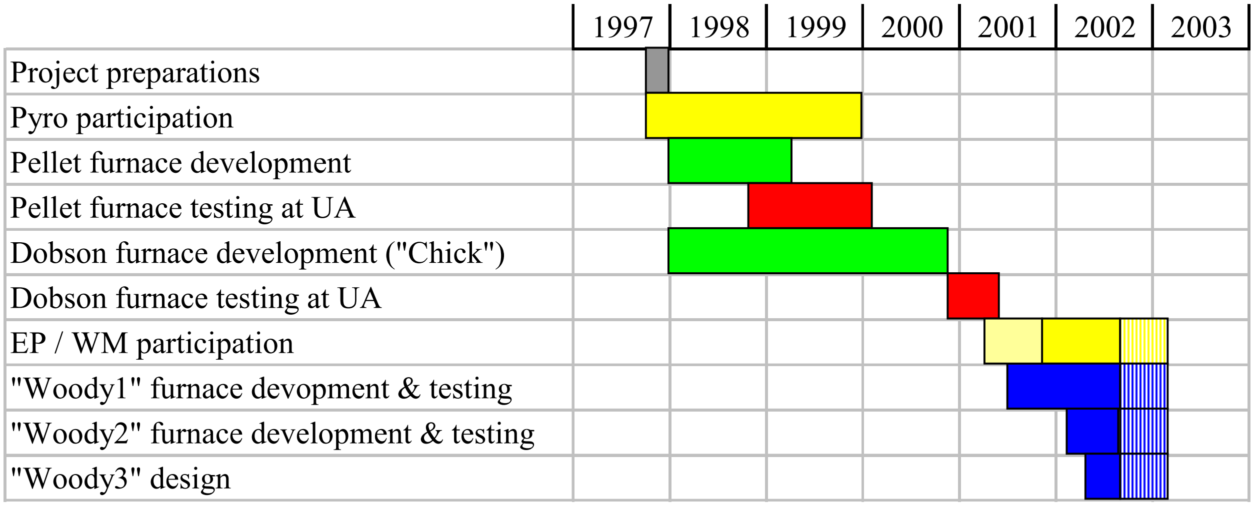
[8] Wood-Mizer's close involvement in the forest products industry, in-depth knowledge of milling residues, and substantial in-house technical expertise and product development, manufacturing, and sales capabilities provided EP [and this project] with substantial support regarding the woody residue-fired furnace system.

application. As a result, EP/WM formally participated in this project as the new commercialization partner from November 2001 through August 2002.[9]

1.6. Project Activities

The principal activities and participant involvement in this project are shown in the task-timeline set forth in Figure 2. The vertically-striped sections in 2002~2003 reflect continued efforts (and associated investments) regarding furnace product development by EP/WM beyond the project sub-agreement period.

Figure 2: Project Task-Timeline



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[9] Through this project EP/WM developed and tested a third-generation furnace unit referred to as "Woody2" and began designing a fourth generation unit, "Woody3". Since the expiration of EP's subcontract in August 2002, EP/WM has continued its efforts to develop the furnace technology (using woody residue fuels).

2. Results

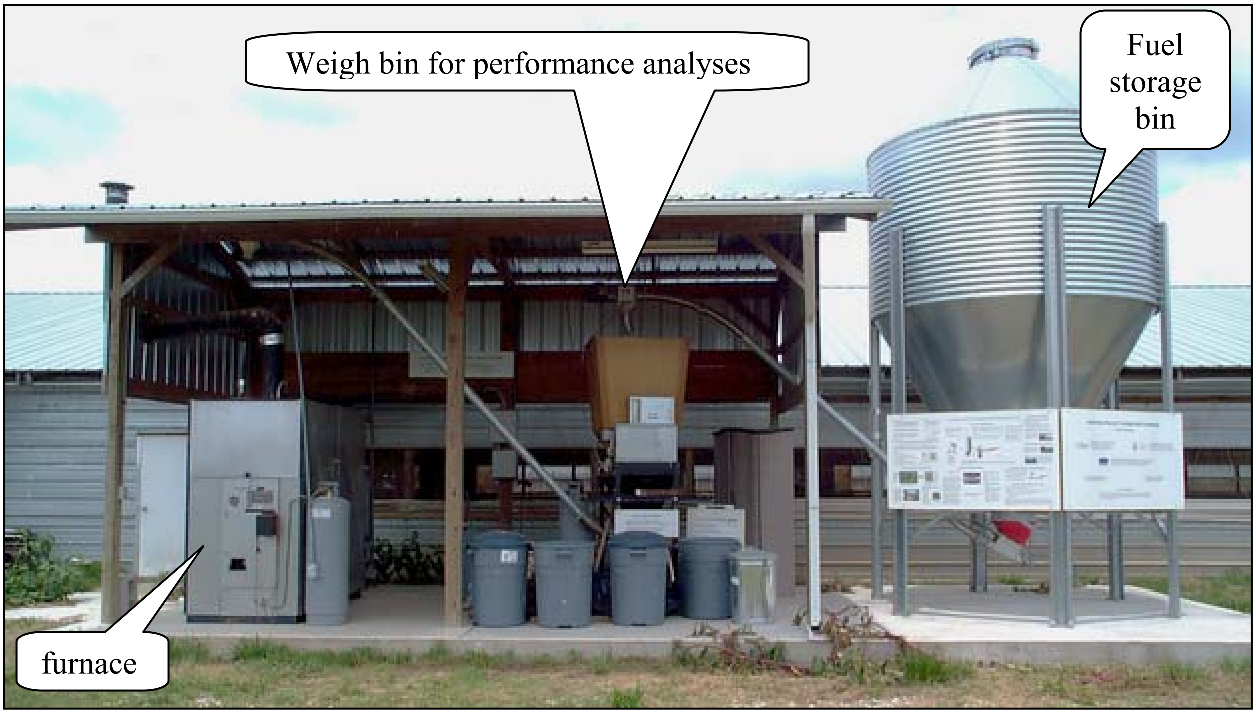
2.1. Overview

Four prototype furnaces were developed & tested: one pellet-fired energy system (the Pyro unit) and three subsequent generations of an unprocessed biomass energy system (Chick, Woody1, and Woody2).

2.2. Pyro's Pellet-fired System

The unit was developed between early 1998 ~ mid-1999, and installed at UA and test-operated during the Fall of '99. Figure 3 depicts the installed system. Additional photos of this system are shown in Appendix 1.

Figure 3: Pyro's Pellet-fired System



Performance analysis of this unit was incomplete due to the early withdrawal of Pyro from the project (refer to section 1.5). Overall, this was considered a simple yet potentially reliable system, reflecting the key advantages of using pellets vs. unprocessed woody sawdust or litter. The main technical glitch encountered during initial operations was frequent failure of the fuel intake metering system. Plans developed to address these problems were not pursued after Pyro's early withdrawal and subsequent termination of technical support for the prototype.

As anticipated (and as discussed in detail in section 3.6), the economics of a pellet-fired system are not attractive under current conditions, although the relatively high convenience and reliability factors remain undeniable. The key economic challenge associated with a pellet-fired system is the cost of the fuel, including transport to/from a pelletizing plant as well as the cost of pelletizing. More efficient (and, therefore, less costly) pelletizing technologies are needed. The concept of a mobile pelletizer is particularly attractive in that the costs associated with transport of low-value material to/from the farm and a pelletizing facility could be eliminated.[10]

2.3. Dobson's "Chick"

Larry Dobson first began developing the underlying concepts of this furnace in the 1970s. Several versions were developed & tested prior to this prototype, which was developed during January 1998 ~ December 2000. Initial performance was tested during January ~ May 2001 at the UA Broiler Energy Research Facility. Figure 4 depicts the system installed at UA. Additional photos of this system are shown in Appendix 2.

Numerous difficulties were encountered when testing the system with both green sawdust and litter feedstocks, limiting the team's ability to achieve steady-state operating conditions and obtain meaningful data regarding the unit's performance parameters. The difficulties reflected design, fabrication, and controls aspects – addressing those problems required resources not available to/within the project's technical performance assessment team. However, the unique design and potential benefits of the system became apparent and the associated potential for improving the system and eventually commercializing it was sufficiently high to get the attention of EP/WM during their site visits in April ~ May 2001.

Figure 4: Dobson system installed at UA

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[10] The cost of developing and operating a mobile pelletizing system would likely be much less than the cost of transporting raw material from each farm or sawmill to a pelletizing facility and then back to those same farms.

2.4. EP / WM's "Woody1"

Numerous improvements relative to the first generation unit ("Chick") were incorporated into Woody1 by External Power / Wood-Mizer, including improved design, improved fabrication of components, and improved controls system and operations management. Woody1 was installed and tested at Wood-Mizer's research and development facility in the Fall of '01. Most of the testing was made using clean woody residues – white oak chips and shredded white oak residue processed by a RotoChopper (having an appearance similar to mulch); the system performed much better with the chips, although bridging of the feedstocks in the throat of the unit continued, requiring additional modifications to the vertical fuel intake component.[11]

Figure 5 depicts Woody1 at Wood-Mizer's facility in Kentucky. Additional photos of Woody1 are provided in Appendix 3. With reference to Figure 5: 1) The feed bin included a mechanism for eliminating bridging of the feedstock; 2) An existing belt conveyor was used for supplying fuel to the furnace – the existing conveyor was known to be over-sized, and a correctly sized unit was used with Woody2; and 3) The unit's hot air output was exhausted to ambient during initial testing, but subsequently ducted into the research and development facility for space heating.

Figure 5: Woody1 at WM's research and development facility

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[11] Bridging is an undesirable phenomenon that occurs when the feedstock material hangs up within a storage or conveyance device, resulting in reduced or eliminated gravity flow of material downward within the device.

Test trials with litter feedstocks resulted in severe slagging, although it was later determined that the slagging was aggravated by the use of rice hull-based litter (wood shavings-based litter would likely have resulted in less slagging). Nonetheless, the slagging experience was so negative that EP/WM elected to focus their subsequent product development and commercialization efforts on woody feedstocks-fired units and to re-visit litter feedstocks and pursue a litter-fired system after the wood-fired units had been commercialized.

The system in Kentucky was demonstrated to approximately fifty poultry growers, poultry industry representatives, and technical assistance agency staff in November 2001. Participants expressed high interest levels in potential use of the system, subject to finalization of research and development efforts and commercialization of a technically reliable and economically feasible system. Note that, as of November 2001, poultry growers in Kentucky were not facing the same high levels of concern regarding litter management and water quality issues as growers in older and more concentrated production areas elsewhere in the U.S. such as the Ozark Highlands Plateau. Moreover, the overall region is heavily wooded and has an active forest products industry. Accordingly, growers at the demonstration were primarily interested in woody feedstocks-fired units, whereas growers in other regions seeking surplus litter management options have expressed higher interest in litter-fired units.

2.5. EP / WM's "Woody2"

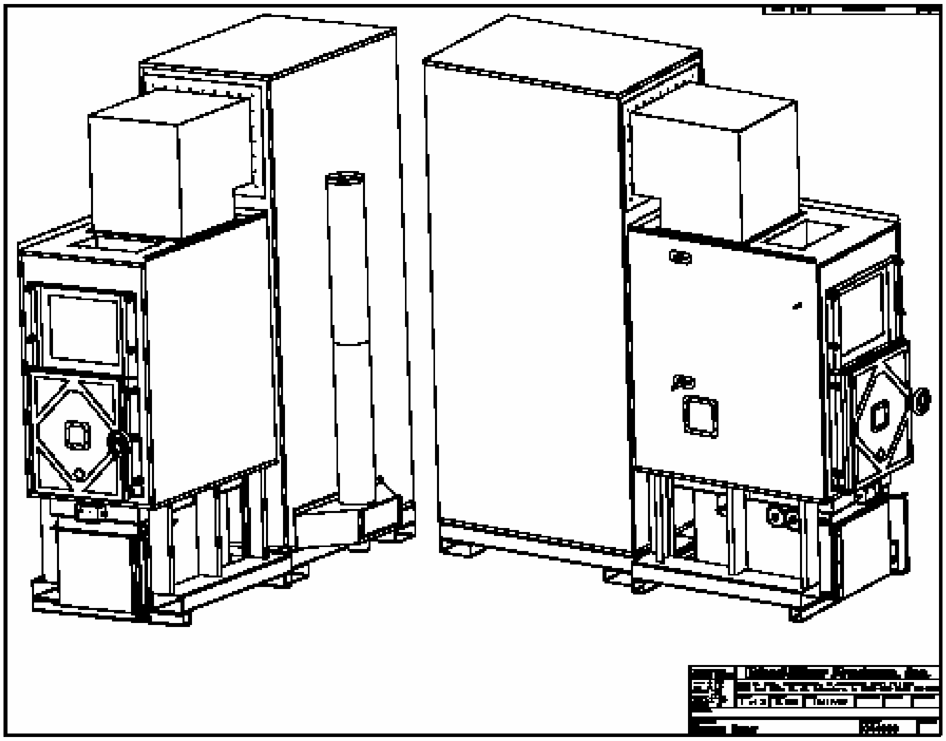
Additional improvements (design, fabrication, and controls) were incorporated into Woody2 based on lessons learned from operational experience with Woody1. The third-generation system based on the original Dobson design and intended for use with unprocessed biomass was initially installed and tested at Wood-Mizer's headquarters in Indianapolis, Indiana, primarily using premium woody fuels (i.e., dry oak chips). Figure 6 shows Woody2 installed in Indianapolis; additional photos of Woody2 are set forth in Appendix 4.

2.6. EP / WM's Woody3

EP / WM began designing Woody3, the fourth-generation system based on the original Dobson design, during this project. The final design was to reflect lessons learned from each of the previous generations, with a continued feedstock focus exclusively on woody residues. EP / WM's illustration of Woody3 is depicted in Figure 7.

Figure 6: EP / WM's Woody2

Figure 7: EP / WM's Woody3 design
(left and right 3-dimensional views)



3. Discussion

3.1. Biomass Feedstocks

The project's target feedstocks were low-grade sawdust and poultry litter. Furnace systems were pursued that could utilize these feedstocks in either unprocessed ("raw") form or processed (pelletized) form. Pelletized feedstocks have numerous advantages, but the cost of the pelletizing process is high (refer to Section 3.5), making the pelletizing option more expensive under current conditions.[12] Descriptions of the primary feedstocks of interest – unprocessed broiler litter, unprocessed green sawdust, wood pellets, and litter pellets – are set forth below. Note that, for convenience purposes, premium feedstocks (e.g., dry white oak chips) were used by EP/WM for testing purposes as described in section 2.

3.1.1. Poultry Litter

Litter is a mixture of bedding material and manure. For a typical broiler operation, approximately 4 ~ 6 inches of bedding is applied on the earthen production house floor and is removed after about one year, i.e., after about 6 flocks have been raised on the material. The preferred bedding material is pine shavings, although substantial quantities of rice hulls are often used in the Northwest Arkansas region. The two materials are often mixed with ratios typically varying from 25% ~ 50% hulls.[13] It is estimated that as many as forty percent of the broiler houses in the region use at least some rice hulls. This is significant in that the silica in the rice hulls enhances the potential for slagging within a litter-to-energy system, particularly when the silica combines with phosphorus/potassium contained in the manure. Thus, to minimize problems within the combustor/gasifier, shavings-based litter is a preferred feedstock compared to hull-based or mixed bedding-derived litter.

A typical 40-foot by 400-foot broiler house will produce about 20,000 broilers per flock, which usually takes 6~7 weeks. Some of the litter inside the house clumps up, particularly in areas under the watering lines. Such clumps or clods are commonly referred to as "cake." The cake is usually removed between flocks using a specialized piece of farm equipment known as a de-caker. A total of about 130 tons of litter is generated per house each year, of which about 30 tons is cake (i.e., approximately 6 tons is removed from the house after each flock, with total cleanout of the remaining 100 tons of litter at the end of the sixth flock). Note that these figures are considered typical for the Ozark Highland Plateau region, although the actual amount of litter/cake removed from broiler houses varies substantially, depending on a variety of factors. In fact, in recent years the region's industry has moved towards more infrequent total clean-out, e.g., once every two years.[14]

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[12] This could change if a more cost-effective pelletizing technology becomes available.

[13] Anecdotal information indicates that the hull/shavings ratio has been increasing (e.g., to 80%/20%).

[14] Clean-out cycles vary throughout the country. In some regions of concentrated production, total cleanout every two years is considered typical, whereas some growers/integrators prefer to clean out after each flock. In southern

Historically, both the cake and the litter have been directly applied to agricultural lands on or near the production farm immediately after de-caking and cleanout (when possible, such cleanout events have occurred in the early spring so as to maximize the agronomic benefits of the material). But in the past ten years or so, an increasing number of poultry farms have constructed litter/cake storage buildings, commonly referred to as stacking sheds. These buildings are usually sized to hold the total cleanout quantity, thereby enabling the farmer to store the material for subsequent land application when desired, regardless of when the cleanout occurs. It is anticipated that the number of farms with stacking sheds will continue to increase, particularly since the stacking sheds enhance a grower's ability to pursue surplus litter management options (e.g., export, or on-farm use such as a litter-to-energy system). Thus, stacking sheds can serve as long-term bulk storage for litter – an important function vis-à-vis potential deployment of on-farm energy systems.

The nature of litter varies substantially, due to a wide range of factors. A description of "typical" broiler litter, including key constituents, is shown in Appendix 5. From an on-farm energy perspective, some key characteristics of "typical" litter include:

- Energy content: about 4,600 Btu/lb *as is*.
- Moisture content: ranging from 17% ~ 35%, averaging about 25%, wet basis.
- Ash content: about 20% (by weight).
- Odiferous (particularly if it gets wet) and contains pathogens.
- Corrosive (both from direct physical contact as well as from ammonia and/or other off-gasses emitted as a result of biological degradation during storage).
- Should be stored under roof (or tarp), and should not be stored over 5 feet deep due to its high potential for spontaneous combustion.
- Can easily bridge within a materials-handling system – containers should have vertical or even negative-slope sides and, if feasible, be lined with low-friction material.
- High slagging potential due to high phosphorus, potassium, and/or silica content.

As evidenced by the foregoing, broiler litter has considerable energy value, but it also has numerous other characteristics that detract from its attractiveness as a fuel and make storage, handling, and combustion/gasification potentially difficult. Clearly what makes this material desirable as a potential fuel is its availability (the fuel is already on the farm), its low cost, the increasing need to pursue surplus litter management options (in those areas of concentrated production that have surplus litter), and the potential opportunity to avoid the cost associated with export of surplus litter from the production farm.

Texas, the poultry industry has embraced a very long clean-out duration, with some houses not receiving total clean-out until after fifteen or even twenty years.

3.1.2. Sawdust

Sawmills throughout the Ozark Highlands Plateau (and in several other areas of concentrated poultry production in the southeastern U.S.) are generally much smaller than the large industrial facilities found in southern Arkansas and northern Louisiana; as such, they are generally unable to justify purchase/use of on-site systems that convert the sawdust and other milling residuals into thermal/electrical energy. Since use of on-site incinerators was discontinued due to regulatory concerns regarding air emissions, the common management practice for sawdust generated at such facilities has simply been accumulation…the material is piled up near the processing facility, with the residue piles growing larger as operations continue. Without locally available markets or other disposal options for the low-value material, this material has become a management burden for the facilities.

The nature of the sawdust generated at these relatively small sawmills varies, although it is almost always green (high moisture content) and derived from hardwoods, not softwoods (again, in contrast to the residues generated by large mills in the south, which are primarily from softwoods). From an on-farm energy perspective, some key characteristics of this low-grade sawdust include:

- Energy content: about 4,600 Btu/lb *as is*.
- Moisture content: typically about 50%, wet basis (additional moisture can come from rainwater, since most of the sawdust piles at the mills are uncovered).
- Ash content: varies from 1%~8% (by weight), depending on numerous factors such as bark content and amount of soil in the bark (from logging operations); an average of 5% has been assumed.
- Contains bark and occasional off-cuts (and sometimes other contaminants such as tools or parts from the sawmill; this necessitates visual inspection when loading/unloading and perhaps even screening if contaminant levels are problematic).
- Should be stored under roof (or tarp) to minimize additional wetting from rain.
- Can easily bridge within a materials-handling system – containers should have vertical or even negative-slope sides and be lined with stainless steel or some other low-friction material.
- Lower minerals content and, therefore, lower slagging potential than litter.

The primary factor affecting the fuel quality of low-grade sawdust is its high moisture content. The material's fuel quality will further deteriorate over time due to naturally occurring biological degradation, particularly when in deep piles and exposed to the elements. Refer to Appendix 6 for photos of typical low-grade sawdust.

3.1.3. Pelletized Sawdust

Pelletized sawdust has numerous significant advantages relative to unprocessed sawdust, including, in particular, uniformity and homogeneity of physical, biological, and energy attributes. The only real drawback is economics, since the sawdust must be transported in raw form to a pelletizing facility, processed, and then transported to the broiler farm – each step incurring significant cost. Key benefits of wood pellets include:

- Energy content: about 8,500 Btu/lb *as processed.*
- Moisture content: typically about 10% or less, wet basis.
- Ash content: less than 1% (premium-grade wood pellets are less than 0.5%).
- Uniform physical characteristics: Pellets can be manufactured in different diameters, ranging from 1/8” to ¾”; the typical size of most wood pellets is ¼” diameter, with and an average length of ¾” to 1”.
- Ease of storage and handling: Pellets can be transported from mills to farms in existing grain trucks (used daily for delivering pelletized feed to poultry houses), stored in off-the-shelf hopper-bottom grain bins (used for feed storage on broiler farms), and handled using off-the-shelf open-coil tube augers (also used on broiler farms for feed conveyance). Pellets will physically deteriorate almost instantly if they get wet.
- Ease of use as a fuel: Wood pellets can be easily metered into an energy system, thereby facilitating the system’s design and operation.
- Availability: Pellets can be purchased in bulk and transported from wood pellet manufacturing facilities; there are over fifty such facilities in North America. The three facilities nearest poultry production areas in the Ozark Highlands Plateau are in Greenfield, Missouri; Springfield, Missouri; and Pine Bluff, Arkansas.[15]

Biologically, wood pellets are very stable with long shelf life, having been dried to 10% moisture content or less during processing. The consistency and homogeneity of pellets enables optimal design of energy systems (the units don’t have to accommodate variability in fuel characteristics and quality). And the ability to utilize off-the-shelf storage and handling equipment that is already familiar to broiler producers is significant.

One drawback of wood pellets vis-à-vis the project’s goals is that only high quality sawdust is used as a feedstock for pellet production (i.e., generally not the low-grade sawdust produced by small primary sawmills that typically has higher contaminant and ash contents than sawdust from, say, residues from secondary forest products manufacturing facilities (e.g., furniture manufacturers that use clean, kiln-dried oak as their raw material).

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[15] Over one million tons of wood pellets are manufactured each year in North America, primarily as fuel for residential pellet-fired stoves and fireplaces.

3.1.4. Pelletized Litter

Pelletized litter has similar advantages relative to unprocessed litter as do wood pellets to sawdust. The primary drawback is economic, since the litter must be transported in raw form to a pelletizing facility, processed, and then transported back to the broiler farm – each step incurring significant cost. The key benefits of litter pellets are similar to those of wood pellets, except:

- Energy content: about 6,000 Btu/lb @ 10% moisture content.
- Ash content: about 20%.

Pelletized litter has all of the storage and handling benefits of wood pellets, except that the material still has some odor (even though the pathogens are effectively eliminated during processing). Like wood pellets, litter pellets will disintegrate if the material gets wet. In addition, wet litter pellets will likely become biologically active again, go anaerobic, generate significant odor, and become difficult to handle or remove from the storage facility.

There are only a few litter pelletizing facilities in the United States. Because of the high cost of processing and subsequent transportation to broiler farms (refer to Section 3.5), the economics of using pelletized litter for on-farm energy systems are particularly challenging. Although some tests using litter pellets were undertaken during this project, it is unlikely that pelletized litter-fired systems can be feasible unless there are significant cost-reducing changes in litter pelletizing technologies.

3.2. Technical Considerations

3.2.1. Broiler Production Houses

The quantity, size, design, and orientation of production houses on broiler farms vary considerably. In the Ozark Highlands Plateau, the number of houses per farm varies from one to over ten (refer to Figure 8); the average is generally considered to be four.

The typical older house in this region is 40’ by 400’, with a capacity of about 20,000 birds per flock. Newer houses tend to be somewhat larger—often 42’ by 500’, with capacities of 25,000 ~ 28,000 birds, depending on the size of birds at harvest.

Ideally, the houses are aligned in parallel, with 50’ to 75’ spacing between the houses (refer to Figure 9). In reality, the alignment / spacing / orientation of the houses varies, affected by the farm’s topography and other factors (refer to Figure 10).

Figure 8: Example of variations in farm configuration

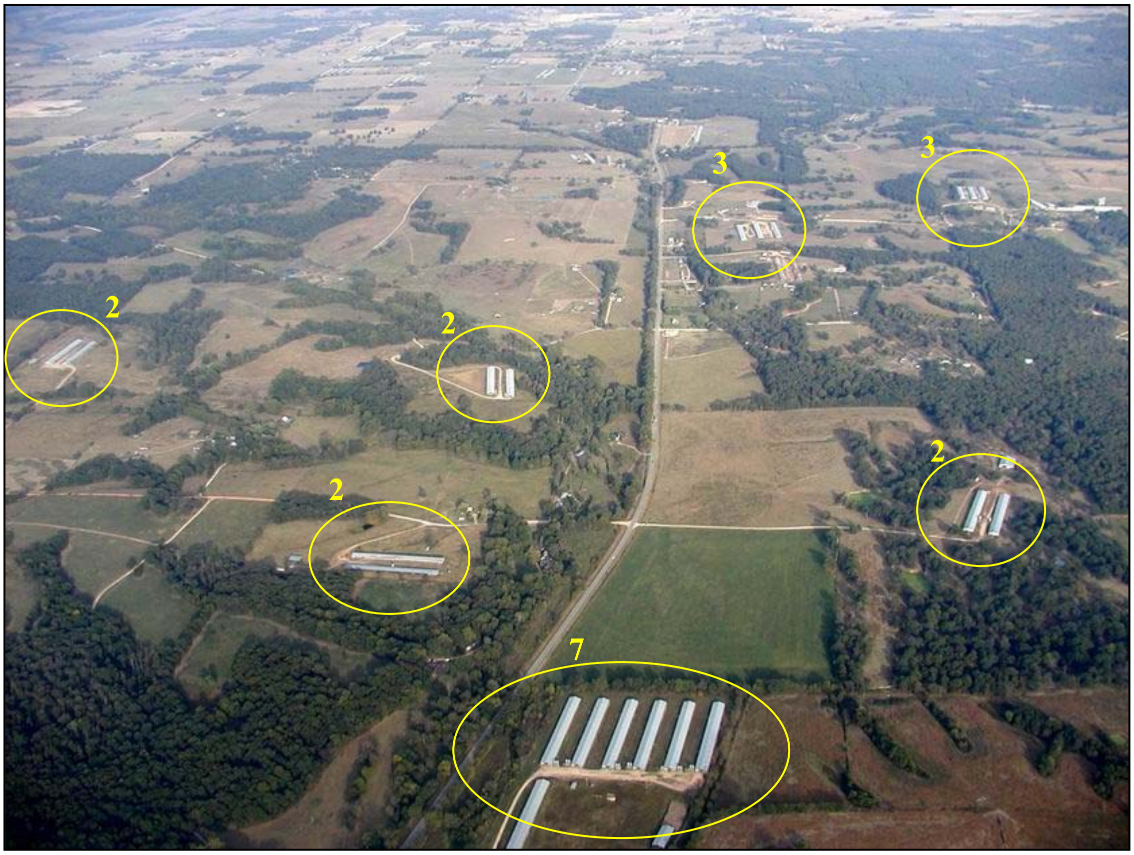

Figure 9: Example of a 4-house configuration with houses in parallel

Figure 10: Example of a broiler farm with houses *not* in parallel

Older houses were typically constructed with open sidewalls covered with plastic drop curtains (refer to Figures 11 and 12). In hot weather the curtains are dropped on both sides for cross-flow ventilation; four 36" fans (usually installed on the north side of the house) are used to enhance cross-flow ventilation (refer to Figure 13). In cold weather the curtains are opened slightly at the top (along the south wall if the ventilation fans are on the north wall), with exhaust of ammonia/dust generated within the house provided by the four fans. Stirring fans (24" and 36" diameter sizes) located inside the houses are often installed to increase ventilation and bird cooling during hot periods (refer to Figure 14). Like most other equipment within broiler houses, the stirring fans are usually suspended from the ceilings so that they can be winched up during bird harvesting. It is estimated that the majority of houses still in use in this region are of this open sidewall, drop-curtain design.

Figure 11: Broiler house using open sidewall drop-curtain design

Figure 12: Close-up of plastic drop-curtain (in half-open position)

Figure 13: Exhaust fan used for cross-flow ventilation

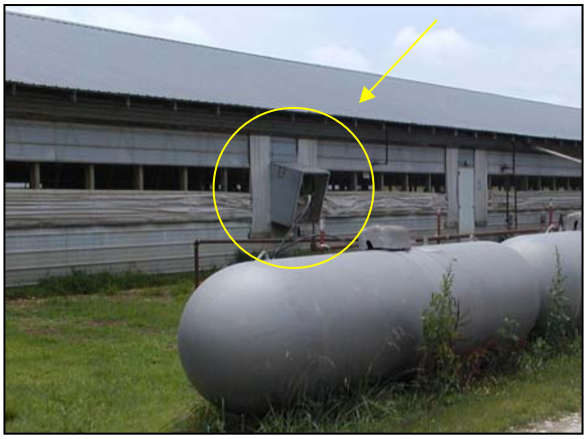

Figure 14: In-house stirring fan (also depicts in-house dust levels)

Newer houses are usually being designed and constructed using the tunnel ventilation design, consisting of solid side walls with exhaust fans located at one end of the building with fresh air intakes at the other end or near the ends of the side walls at the ends opposite of the fans (refer to Figures 15 and 16). Traditional size houses (40' x 400') typically employ eight 48" exhaust fans (@ 20,000 cfm per unit, resulting in a complete air exchange within the house each minute (refer to Figures 15 and 16). Newer and/or larger houses usually have increased fan capacity, e.g., 10 48" fans, resulting in a complete air exchange within the house in less than one minute (refer to Figures 17 and 18). The fans operate intermittently, based on timers set by the farm operator/manager (based on perceived conditions such as ammonia/dust production levels) or set to respond to in-house thermostats. Any heating system must be able to accommodate these high air turnover rates and ventilation control systems. Many integrators in the region recently began requiring their contract growers to convert houses with side-curtain systems into tunnel ventilation systems.

Figure 15: Broiler house reflecting older style tunnel ventilation design (curtains are closed during operation)

Figure 16: Broiler house reflecting newer style tunnel ventilation design (intakes in the middle, 4 fans at each end)

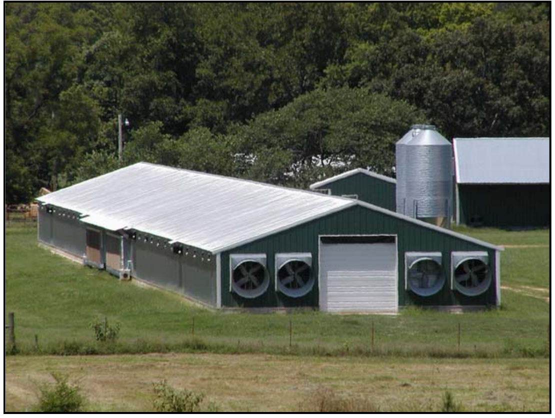

Figure 17: 48" exhaust fans on an older style tunnel ventilated house (this house has 10, not 8, exhaust fans)

Figure 18: 48" exhaust fans on a newer style tunnel ventilated house (this house has 4 exhaust fans at each end)

Tunnel ventilation systems are more effective and efficient than are drop-curtain designs in exhausting dust/ammonia and providing fresh air to the birds, but these designs greatly increase producers' reliance on electric power. More and more, producers have purchased and installed on-farm backup generators, with use of such generators strongly encouraged – and often required – by most integrators (refer to Figure 19). During extreme weather periods, an entire flock of birds can be lost in less than an hour if the heating and/or ventilation system goes down (refer to Figure 20).

Houses employ both open truss and drop ceilings, supported by wood or metal ceiling trusses (refer to Figures 21 and 22). The 4" ~ 6" layer of litter serves as an excellent insulator between the birds and the earthen floor; newer houses have more ceiling insulation.

Figure 19: On-site electric generator & shed

Figure 20: Mortality from a ventilation system failure

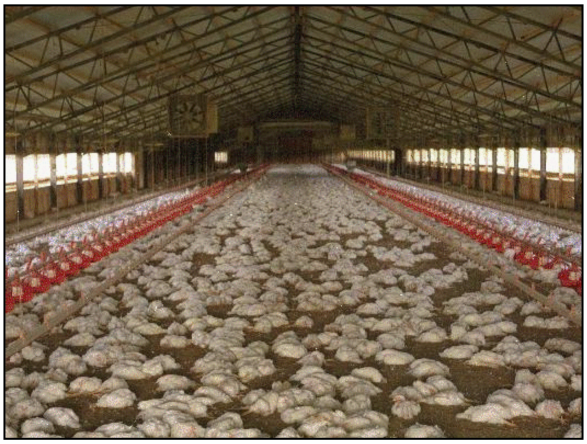

Figure 21: Open-truss ceiling

Figure 22: Drop ceiling

3.2.2. Conventional Gas-fired Heating Systems

As noted previously, almost all broiler houses are currently being heated with gas-fired appliances, mostly using LPG (Liquid Petroleum Gas – primarily propane, although some use butane) and the balance using natural gas. There are two primary types of gas-fired heaters used: brooders and forced-air heaters. Most houses use both types, although some use only brooders. Like all other equipment inside a broiler house (e.g., watering lines, feed lines), the heaters are suspended from the ceiling on thin wire so that the units can be raised up during bird harvesting and between-flock maintenance, including litter clean-out.

The brooders, or "pancake" heaters, are radiant-type heating units suspended to within 2~3 feet of the floor (refer to Figures 23 and 24). The upper shield reflects much of the heat downward towards the birds, with the balance of the heat providing space heating. No fans are used, meaning that the units' effectiveness continues even during power outages. A typical pancake brooder is rated at 30,000 Btu. The brooders are considered particularly effective during the first few days after chicks are placed in the houses, as the birds tend to huddle together underneath and near the units, particularly during extremely cold weather (taking into account the need to rapidly bring in-house temperatures back up to desired levels after exhaust of the conditioned air by the ventilation system).

Figure 23: Pancake brooder (in down position)

Figure 24: Underside view of pancake brooder (in up position)

The key benefits of brooder heaters include: ability to operate without electrical power; effective at providing heat down low where the chicks are; low capital cost; efficient, even in dusty conditions; and proven reliability. Both growers and integrators have high confidence levels in these units. Detailed information regarding brooder heaters is available on the Internet from manufacturers' websites.

Forced air units vary in size from about 120,000 Btu to over 500,000 Btu (refer to Figures 25 and 26). These convection units rely on the fans within the force-air design units to circulate the heated air within the poultry house. Like brooder heaters, all products of combustion are vented within the broiler house, so the heating efficiency of these gas-fired systems is usually assumed to be one-hundred percent.

Figure 25: 120,000 Btu forced air heater (suspended from the ceiling)

Figure 26: 240,000 Btu forced air heater (suspended from the ceiling)

Most broiler houses in the Ozark Highlands Plateau region are constructed with a minimum of 1,000,000 Btu total heating capacity (i.e., the capacity generally believed to be required to meet maximum heating requirements under extreme conditions). Contracts between integrators and growers frequently *require* this capacity at a minimum. Typically a farm's heating needs are met by a combination of brooders and forced-air heaters.[16] For example, house #3 at the University of Arkansas' Broiler Energy Research Facility (UA's BERF) has 30 pan brooders @ 30,000 Btu each and four forced-air heaters @ 120,000 Btu each, for a total installed capacity of 1,380,000 Btu.

New requirements regarding heating systems (types of units, capacities, locations, etc) are made by the region's integrators from time to time, requiring growers to update, modify, or enhance existing heating systems. For example, growers are increasingly required to have at least 20 brooders in that half of the production house used for half-house brooding.[17]

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[16] Many growers have only brooder heaters and rely on these units to meet all of their heating needs, whereas only a few growers use space heaters alone for broiler house heating.

[17] Only half of the production barn is used during the first 10 days or so after chicks are placed in the house in order to minimize heating requirements during this critical period. Almost all broiler houses use a plastic drop curtain located in the middle of the building to separate the two sections.

However, an analysis of fuel consumption data recorded at the UA's BERF over a 16-flock period indicates that approximately eighty-five percent of the heating energy consumed in a typical broiler house can be provided by a system having less than half that capacity (the report, entitled "Use of Liquefied Petroleum Gas in Four Broiler Houses for a Three Year Period, 1990~1993", is shown in Appendix 7). More specifically, as indicated in Figure 27, 85% of the broiler houses' heating energy requirements could be provided by a propane-fired heating system consuming about 3.7 gallons per hour. As shown in Table 1, this level of heating equates to a heating system having 344,100 Btu capacity (assuming the energy content of propane is 93,000 Btu per gallon and that the propane-fired heaters are 100% efficient as previously discussed).

Figure 27: Cumulative Fuel use vs. Rate of Fuel Use for an average of 4 broiler facilities using LPG (propane) fuel

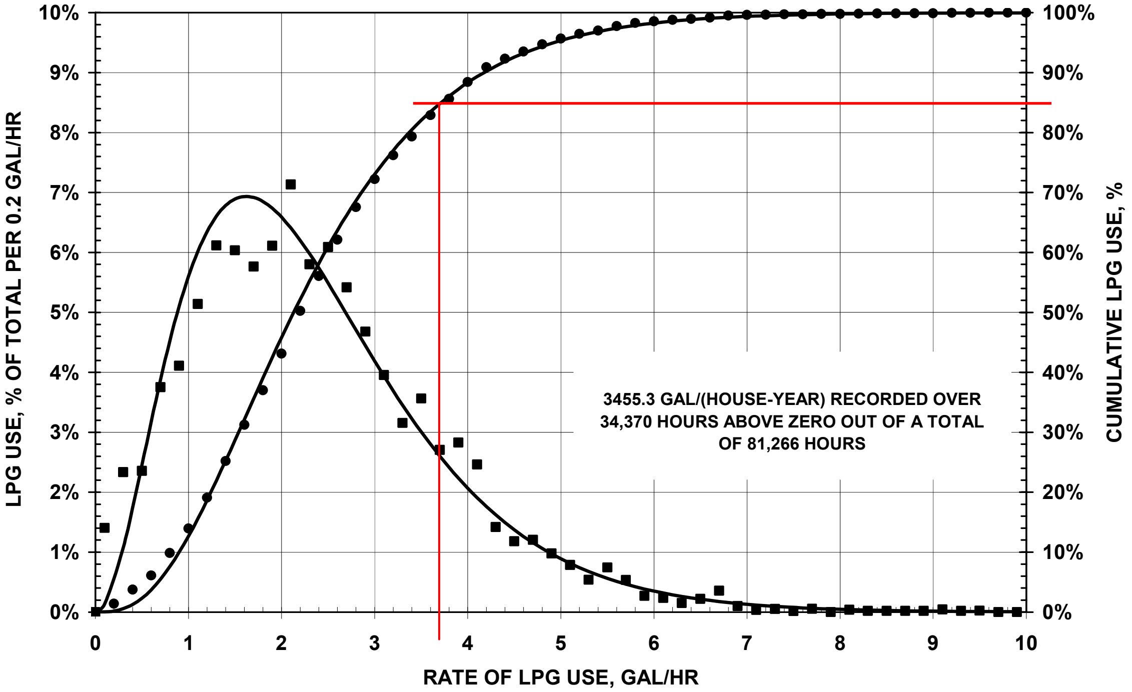

Table 1: Calculation of Required Heating System Capacity for 85% Displacement

fuel consumption @ 85% displacement	3.7	gallons / hour
energy content of propane	93,000	Btu / gallon
gross energy requirements @ 85%	344,100	Btu / hour
energy efficiency of propane system	100%	
net energy output @ 85%	344,100	Btu / hour
energy efficiency of biomass system	65%	
gross energy requirements @ 85%	529,000	Btu / hour

Accordingly, the total required energy capacity for a biomass-fired furnace system having an overall system capacity of 65% would be 529,000 Btu per hour to displace 85% of the fuel used by the existing propane system. Thus, only 15% of the fuel being consumed by an existing gas system would be required to provide the intermittent and infrequent levels of heat required for high-demand periods (i.e., when total heating requirements are greater than the net amount of 344,000 Btu per hour).

An analogy of electrical demand [vs. generation] helps clarify this situation: A house's net energy requirement of 344,000 Btu per hour would represent its "baseload" demand, whereas the house's energy requirement of 1,000,000 Btu would represent its "peak" demand. Thus, a biomass energy system with a rated capacity of 530,000 Btu per hour and a maximum net output of 344,000 Btu per hour would serve as a baseload system providing approximately 85% of the total heat energy demand, with the existing propane system serving as the peak load system, providing the remaining 15% of heat energy demand.

In addition to the maximum furnace output as calculated above, a biomass system must also be able to operate at much lower levels…all the way down to idle. Thus, having a highly variable (and controllable) output or "turn-down ratio" is an essential design criteria for such bioenergy systems. From a design perspective, it is also important to recognize that the bioenergy system, in addition to being <u>on</u> and <u>ready</u> "twenty-four / seven", will have widely varying thermal loads throughout the year and throughout a given flock. Another analysis of fuel consumption at the UA BERF [for a 38-flock period over six years] shows the seasonal variation in fuel demand – refer to Figure 28 and Appendix 8.[18]

With reference to Figure 28, note that propane fuel consumption in house #3 dropped during the 3rd and 4th winters (i.e., the winters of 1998~1999 and 1999~2000) when the pellet-fired furnace was installed and being tested.[19] Of related interest, Figure 29 shows two curves: the average propane consumption for the four houses, and the average electrical consumption (in kWh) for the four houses. As expected, the propane and electrical energy consumption curves are essential inverse functions, representing the high demand for heating in the winter and ventilation in the summer.

Note that the average total fuel consumption for a six-flock period (i.e., one year) during the 6-year data collection period was 5,485 gallons of propane per house and 18,925 kWh per house. The average maximum and minimum energy consumption per flock for the four houses was 83 gallons and 2,875 gallons, respectively, for propane and 1,082 kWh and 6,900 kWh, respectively, for electricity.

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[18] Personal communications with Tom Tabler, manager of the UA BERF; June 2003.

[19] The data presented in the graph shows smooth curves to simulate variations over time; in reality, the data was compiled on a per-flock basis, so a more accurate depiction of the data would be a columnar or staircase function.

Figure 28: Propane consumption for four houses over a 6-year period

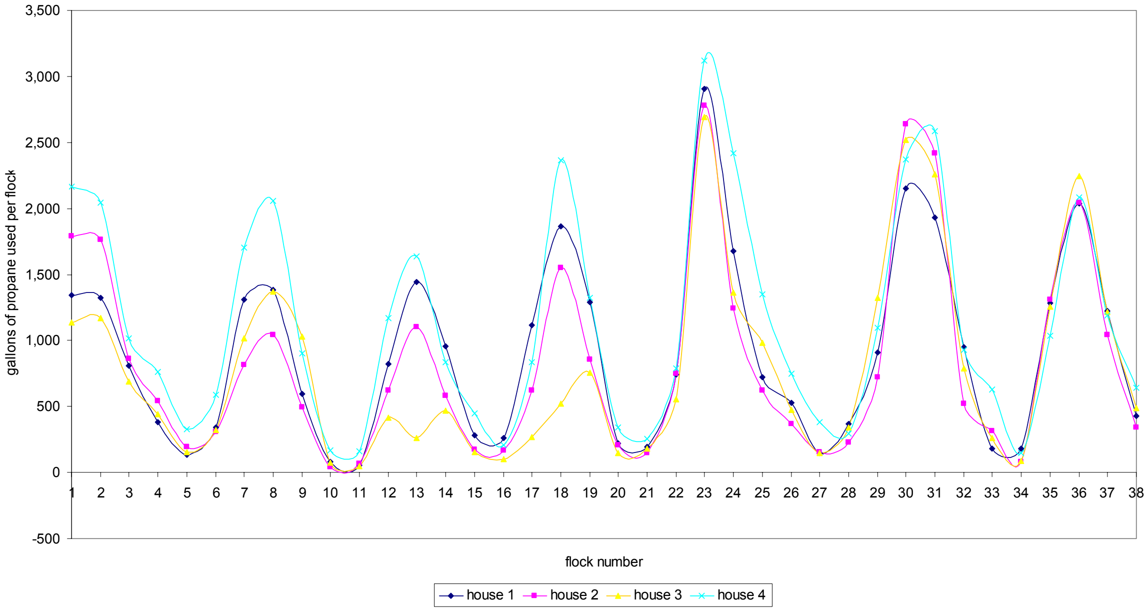
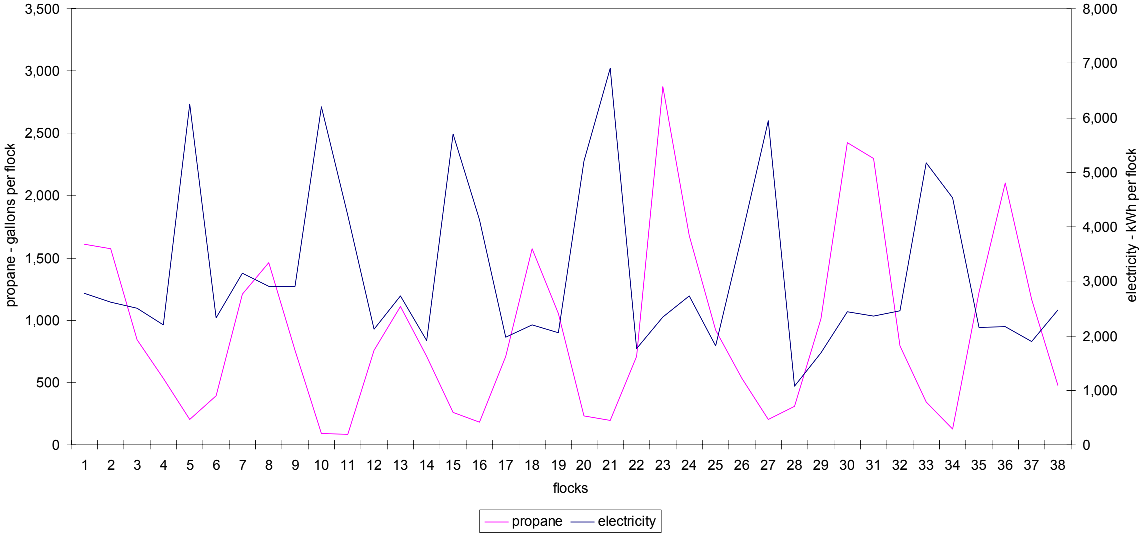


Figure 29: Propane and electricity consumption over a 6-year period



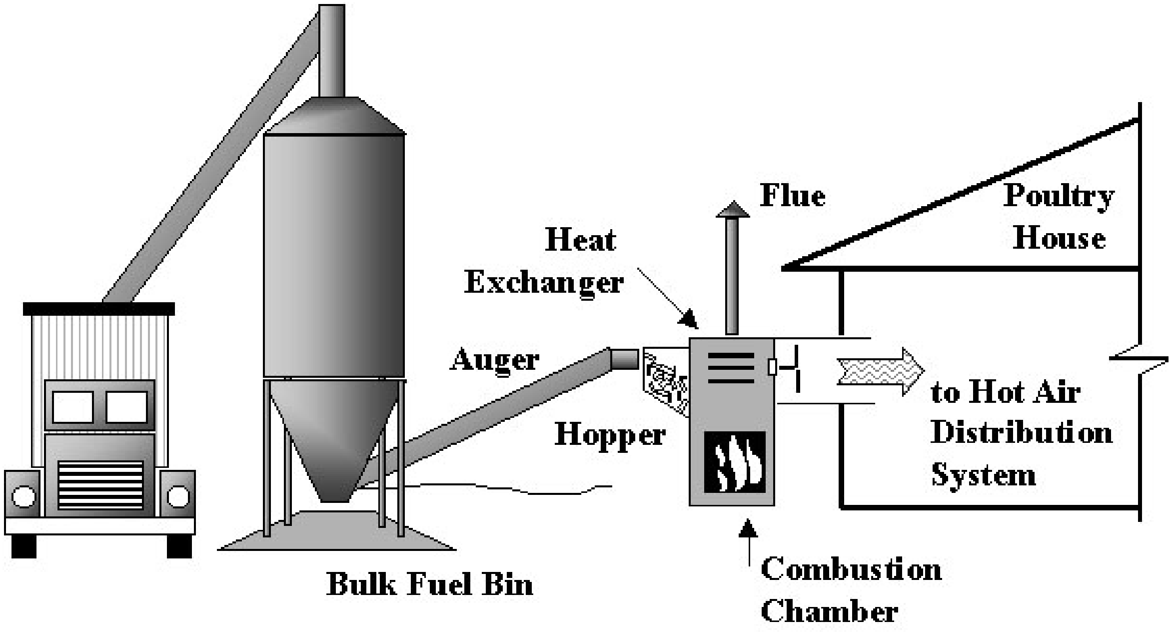
Based on the information set forth above, the target design capacity of a biomass furnace system (regardless of feedstock) has been assumed to be 530,000 Btu per hour, which – serving as a baseload thermal energy system – will displace approximately 85% of the average total quantity of propane used.

3.2.3. Furnace Systems Overviews

Schematics for the two basic furnace system options – pelletized vs. unprocessed feedstocks – are shown in Figures 30 and 31. For a typical four-house farm, there are 3 basic furnace-house configuration options as described below and depicted in Figures 32 ~ 35:

- **1 furnace per house**: This option is the least complex, least costly to design and develop, and easiest to integrate within a farm layout, but probably the least cost-effective option (i.e., the highest in terms of furnace capital and operating costs per house); system design output capacity = 530,000 Btu per hour.
- **1 furnace per 2 houses**: This option entails slightly more complex design (particularly regarding the controls system), but is still relatively easy to design, develop, and integrate within a farm layout; system design capacity = 1,060,000 Btu per hour.
- **1 furnace per 4 houses**: This option entails much more complex design (particularly regarding the controls system and the heat distribution components); a 4-house unit would be more difficult and costly to design, develop, and integrate within a farm layout (particularly given the variations in farm layouts as noted previously); system design capacity = 2,120,000 Btu per hour. However, at least in theory, a 4-house system would be the least costly to manufacture and maintain.

Figure 30: Schematic for a pellet-fired furnace system



With reference to Figure 30, the pellet fuel is delivered in a conventional grain truck (48,000-pound payload capacity) and transferred into the hopper-bottom storage bin using the truck's auger. The fuel is then conveyed from the storage bin via 3" open coil auger to the furnace, which employs an air-to-air heat exchanger. The heated air is delivered to the poultry house for subsequent distribution within. The only differences in the system shown in Figure 31 is that the sawdust is delivered by dump truck and the litter is taken from the on-farm stacking shed, and the material is conveyed to the furnace via belt or drag-chain conveyor.

Figure 31: Schematic for a bioenergy system using unprocessed litter/sawdust

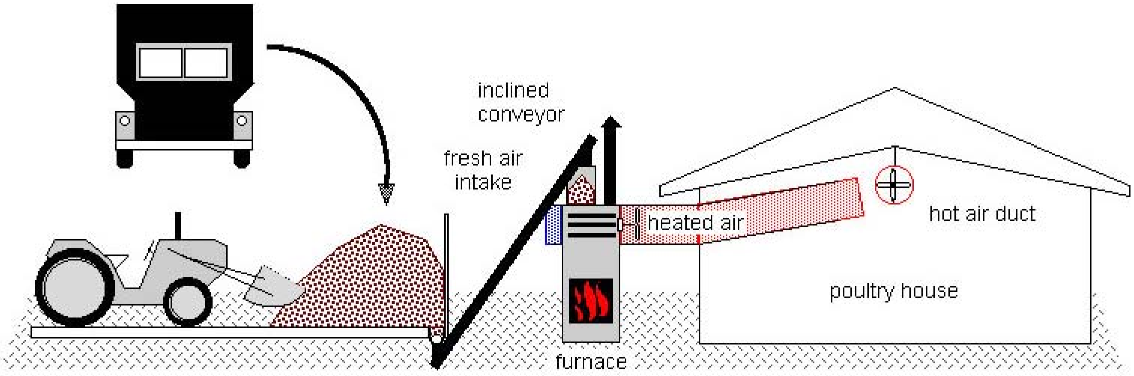


Figure 32: Configuration of a 4-house farm with one furnace per house

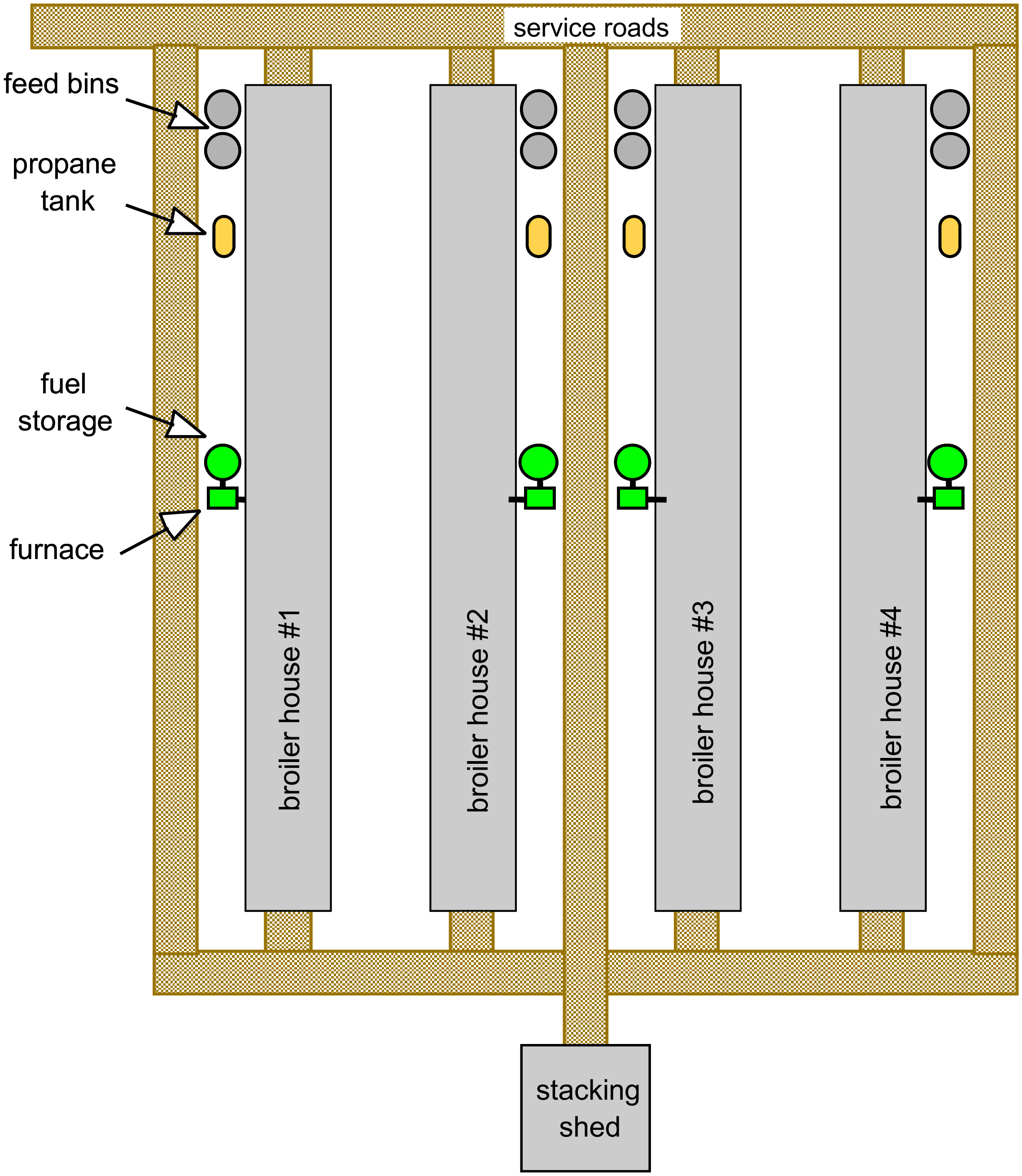
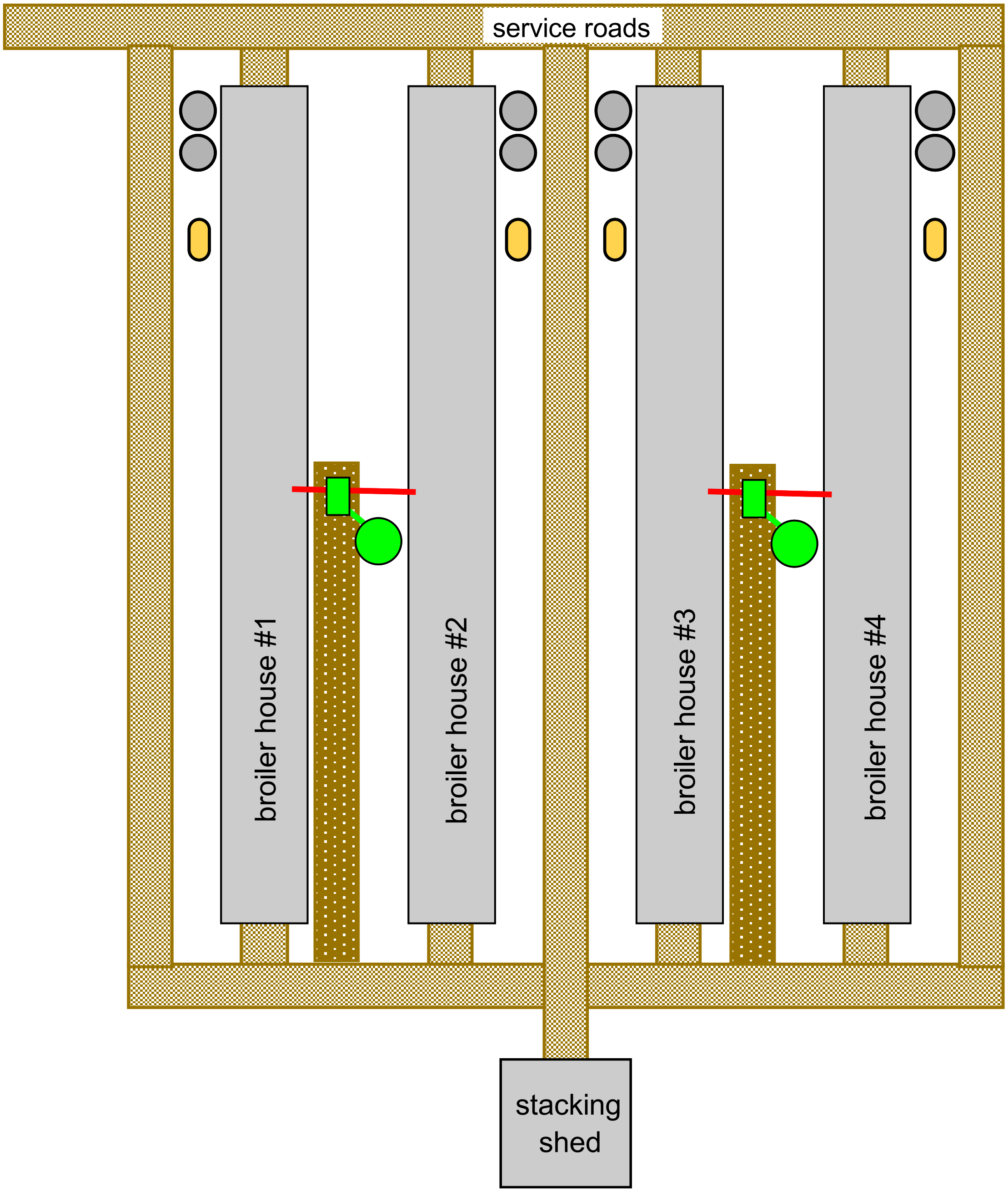
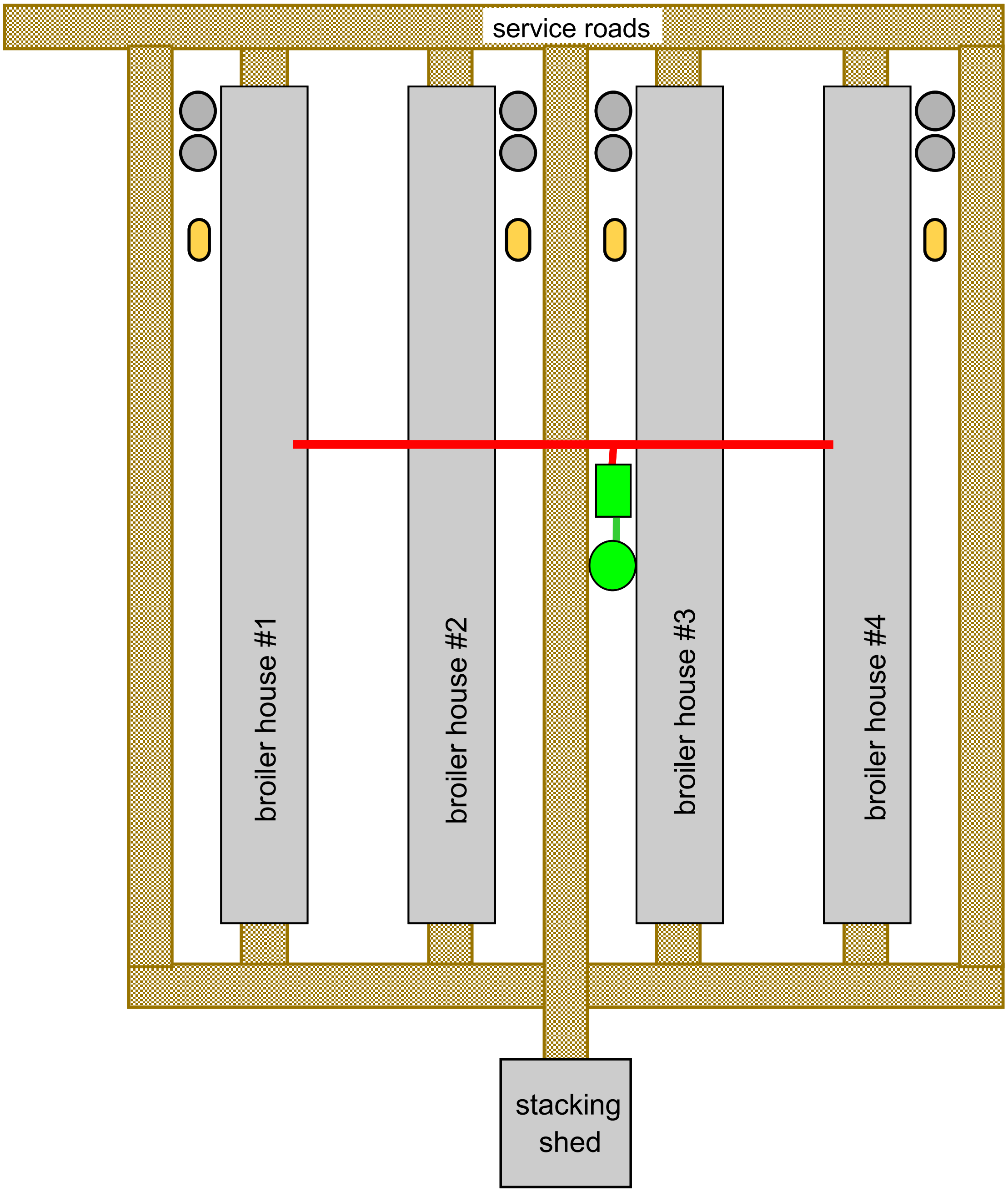


Figure 33: Configuration of a 4-house farm with one furnace per 2 houses



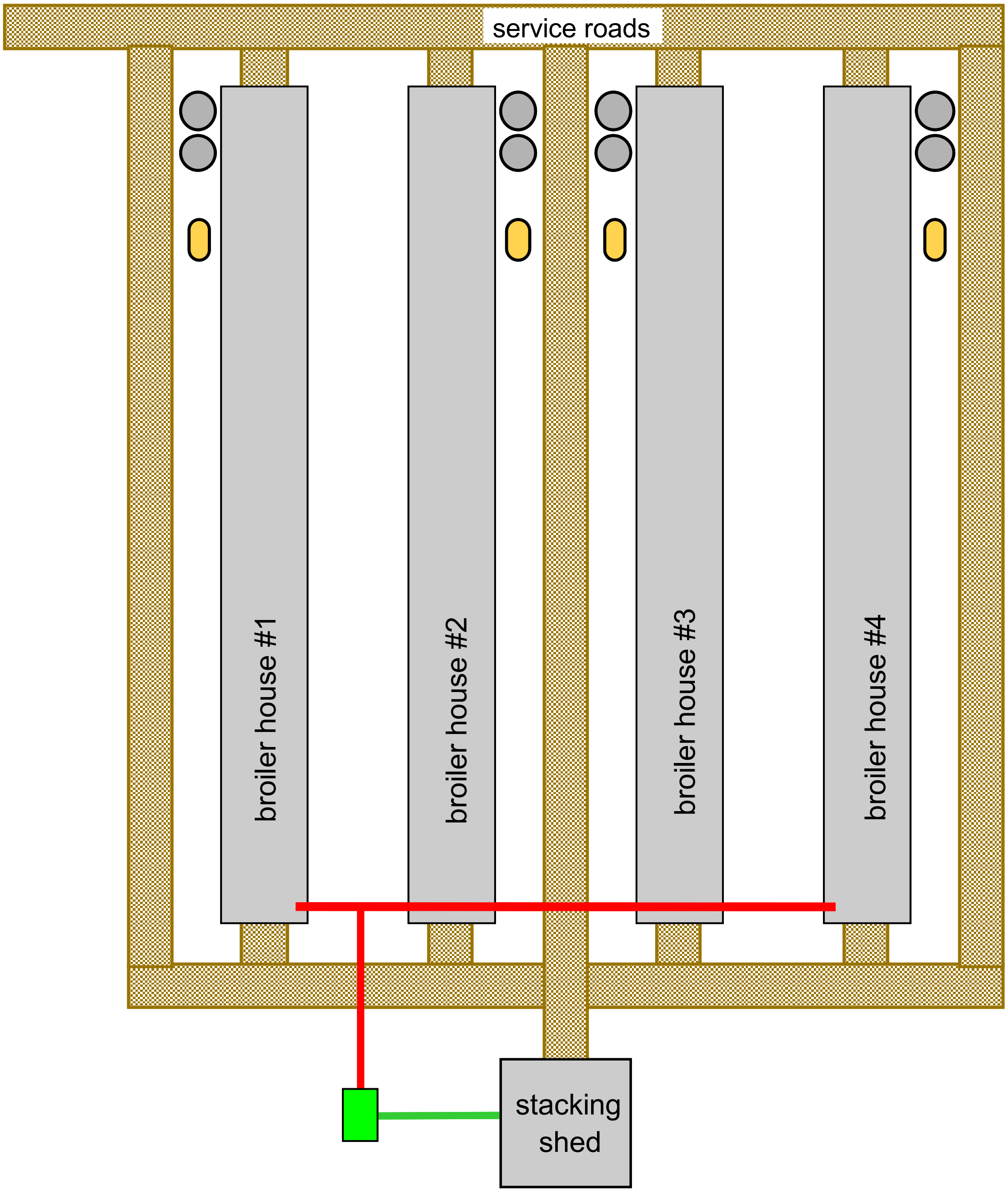
This configuration would require construction of two new service roads to the furnace and fuel storage units, which may or may not be feasible, depending on a particular site's lay-out, topography, soil conditions, etc.

Figure 34: Configuration of a 4-house farm with one furnace per 4 houses, with the furnace [theoretically] located in the middle



The benefit of this configuration is that only one furnace system is required. However, a significant challenge associated with this configuration would be how to convey the thermal energy from the furnace to the outside houses (recognizing that there are only three options: *over* the two adjacent houses, *under* the two houses, or *through* the two houses).

Figure 35: Configuration of a 4-house farm with one furnace per 4 houses, furnace located at one end



This configuration would entail delivering the hot air through ducts to the ends of each of the houses. The logistical challenges are considerable, although probably not as much as with the previous 4-house configuration.

3.2.4. Basic Design Calculations

Key assumptions and basic calculations guiding or affecting system design for each of the three primary feedstocks are shown in Table 2 (key assumptions are shown in yellow, results of calculations in turquoise, and repeated assumptions/results in light purple).

Table 2: Key assumptions and basic design calculations

	wood pellets	broiler litter	low-grade sawdust	
typical current fuel consumption - propane	5,000	5,000	5,000	gallons / year
target displacement level (biomass vs propane)	85%	85%	85%	
quantity to be displaced	4,250	4,250	4,250	gallons
energy content of propane	93,000	93,000	93,000	Btu / gallon
propane system efficiency	100%	100%	100%	
net energy to be displaced	395,250,000	395,250,000	395,250,000	Btu / year
energy content of biomass fuel (as received)	8,200	4,600	4,600	Btu / pound
amount of biomass fuel required	48,201	85,924	85,924	pounds / year
amount of biomass fuel required	24	43	43	tons / year
biomass system efficiency	70%	65%	65%	
total amount of biomass fuel required	34	66	66	tons / year
LPG consumption @ 85% displacement level	3.7	3.7	3.7	gallons / hour
energy content of LPG	93,000	93,000	93,000	Btu / gallon
max system output @ 85% displacement level	344,100	344,100	344,100	Btu / hr
system efficiency	70%	65%	65%	
required system size	492,000	529,000	529,000	Btu / hour
max fuel consumption	60	115	115	pounds / hour
max fuel consumption	1,440	2,760	2,760	pounds / day
max fuel consumption	0.72	1.38	1.38	tons / day
bulk density of biofuel	25	22	20	pounds / cubic foot
max volume of biofuel required	2.1	4.6	5.1	cubic feet / day
total volume of biofuel required	102	223	245	cubic feet / year
required storage capacity	10	10	10	days
required storage capacity	21	46	51	cubic yards
required storage bin length (@ 6' high, 12' wide)		17	19	feet
required storage bin height (@ 6' diameter)	20			feet
required storage capacity	7.2	13.8	13.8	tons
delivery truck capacity (net)	24	24	24	tons
truckloads of biofuel required	0.30	0.58	0.58	per 10 days
truckloads of biofuel required	1.4	2.8	2.8	per year

3.2.5. Fuel Storage and Handling

Fuel storage and handling is a major component of the overall system. The challenges are often under-appreciated, and the cost can be as much – or perhaps even more – than the furnace. Fuel storage and handling systems vary by biofuel.

- **Pellets**: The fuel can be delivered from the pellet mill to the poultry farm by a conventional grain truck (with a typical payload of 24 tons). The pellets are transferred through the truck's on-board auger into a weather-proof hopper bottom silo storage unit (the same silo used for grain storage on poultry farms and readily available through local poultry supply companies). These pre-fabricated silos come in various sizes – a common size is a six-foot diameter, with total capacity determined by the number of vertical rings installed. Typical hopper bottom grain bins are depicted in Figure 36.

  The pellets are conveyed from the silo to the furnace using off-the-shelf open coil tube augers. These augers are available in various diameters, although 3" is a common size (and the size used with the pellet system tested under this project). Figure 37 shows a silo's hopper bottom boot and a tube auger; two extra coils that fit within the plastic tubes are also shown. The bridging potential of pellets is essentially zero, provided the storage silos do not leak and the pellets stay dry. These storage and conveyance units offer maximum convenience & automation.

Figure 36: typical pre-fabricated grain silos that can be used for storing pellet fuel

Figure 37: silo hopper bottom with tube auger (and extra open coils)

As shown in Table 2, the required storage capacity for wood pellets wood be 7.2 tons for a 10-day supply at maximum system output for the entire 240-hour period (considered a highly unlikely scenario). For a 6' diameter bin, this would require a 20' height (excluding the volume contained within the hopper).

- **Sawdust**: The fuel can be delivered from the sawmill to the poultry farm in a dump truck or similar carrier. There are limited on-site storage options: an open (or covered) bunker, requiring some method of transferring the material from the bunker to the furnace; or a large container with a bottom chain-drag conveyor for unloading the container into a second conveyor for transferring the material to the furnace.

  For this project a long open bunker was constructed, consisting of a 12' wide by 24' slab with 4' sidewalls made of treated wood (refer to Figure 38). The material was dumped in the bunker by the delivery truck, then transferred to a modified forage wagon by front-end loader (most poultry farms have a front-end loader on-site). The wagon was custom fabricated with the container portion separate from the chassis, enabling load cells to be installed under the container to monitor fuel consumption.

  The forage wagon used a drag-chain conveyor along the bottom, which discharged the material into a perpendicular 12" screw auger at the end, which discharged the material into an inclined screw auger that fed the furnace. Because the screw augers were prone to plugging, use of drag-chain or belt conveyors is recommended for other installations.

Figure 38: Sawdust / Litter fuel bunker

- **Litter**: The fuel can be transferred from the on-farm stacking shed to the interim storage bunker using the farm's front-end loader, then from the bunker to a fuel feeding container (such as the modified forage wagon used for this project) also using the farm's front-end loader (or, if the container has sufficient capacity, the material can be transferred directly from the stacking shed to the feeding container, bypassing [or eliminating the need for] the bunker). A typical stacking shed is shown in Figure 39.

Another possible option might be to devise a fuel feeding system that utilizes an existing litter spreader (whether a spreader truck or spreader trailer). For example, the material could be discharged from the spreader in a conventional manner, but discharged against a wall (constructed of wood or concrete); after exiting the spreader through it's spinners, the material would hit the wall and drop down into a lower chute with a chain-drag or belt conveyor for subsequent conveyance to the furnace. Such a system could utilize existing widely available litter spreading machinery. Alternately, the same receiving configuration could be designed to receive litter directly from the front-end loader (after obtaining material from the stacking shed).

One additional benefit to using farm-derived litter as fuel is that the size of the fuel storage unit adjacent to the furnace could be minimized, assuming full-time availability of the farm's front-end loader. Accordingly, the minimum storage capacity of 10 days assumed in Table 2 could be reduced to, say, 3 days, which would require a surge litter storage unit (e.g., a modified forage wagon or litter spreader) with a capacity of about 4 tons or 14 cubic yards).

Regardless of which storage and handling system is utilized next to the furnace, it is essential to design and construct the system so that the litter will not get wet. Litter is highly prone to bridging (in fact it will almost certainly bridge within any storage system if left for even just a few days), and will quickly go anaerobic and become extremely difficult to convey if wet. Moreover, high moisture would greatly reduce the fuel characteristics of the material (and increase its probability of bridging *within* the furnace system).

Figure 39: Litter Stacking Shed
The building on the left is a broiler house.

3.2.6. Furnace Design and Operations

In addition to the various assumptions previously discussed, the following criteria were used to guide design of the furnace systems:

- Each system would be installed outside of the broiler house and would use outside combustion air. It had been concluded from previous experiences with other poultry house furnaces that locating the furnace inside (primarily to capture the unit's radiant energy) was not practical from installation and maintenance perspectives (including interference with bird harvesting and litter clean-out), and that use of inside air required an unacceptably high level of filter maintenance due to the extremely dusty conditions within a broiler house. It is further assumed that the small amount of positive pressure introduced by such a system using ambient air would be acceptable to the grower.[20]
- Each system would use an air-to-air heat exchanger. It had been concluded from previous experiences with other poultry house heating systems that using a water or steam cycle was impractical, primarily due to the quick plugging of in-house heat exchangers from the extremely dusty conditions within a broiler house.
- Each system would focus, at least initially, on 100% thermal output. Several manufacturers have discussed the possibility of providing a possible option of a heat- or steam-driven electrical generating subsystem to the furnace (particularly for meeting ventilation energy demands during summer [i.e., non-space heating] periods). The challenge of developing and deploying an on-farm biomass-fired generator is exacerbated by the potential liability of flock mortality due to electrical failure, requiring that any on-site system be essentially 100% reliable.
- Each system would also, ideally, serve as a mortality incinerator. This would be a significant benefit to a broiler house operator and would enhance the value of the bioenergy system to a purchaser.
- A pellet-, sawdust-, or litter-fired system would be installed only on farms as a supplemental furnace system to meet the poultry houses' "base load" thermal requirements (i.e., target displacement of 85% of historical propane/ natural gas consumption) and that the existing gas system would continue to be used for peaking purposes (i.e., approximately 15% of total thermal energy requirements) and to serve as a backup in the event of failure of the bioenergy system. Thus, bioenergy systems would be targeted at existing operations rather than new installations.

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[20] Concerns have been expressed by some growers/integrator staff that positive pressured houses can negatively impact bird production; however, FORM was not able to identify any scientific evidence to support this, and most growers/integrator staff felt that such small positive pressure would not be a problem. In fact, some faculty and staff at the University of Arkansas noted that such a system could reduce ventilation requirements by providing a small amount of fresh air during system operation.

- A pellet-, sawdust-, or litter-fired system would be installed on a farm that has an electric generator and that the generator would be able to run the furnace system in the event of disruption of grid service.
- A sawdust- or litter-fired system would be installed on a farm that has a front-end loader and that the front-end loader would be available for transferring sawdust/litter from the storage bunker or stacking shed to the furnace fuel supply systems (e.g., a modified forage wagon).
- A litter-fired system would be installed on a farm that has a stacking shed.
- The primary control input for the system would be an in-house thermostat set by the farm manager.

A pellet-, sawdust-, or litter-fired furnace would have the following components/attributes:

- Fuel intake (& drying)
- Ignition (e.g., automatic use of auxiliary propane for start-up)
- Primary / secondary combustion
- Variable operating levels (high turn-down ratio, not on/off)
- Air-to-air heat exchanger
- Heated air output blower
- Exhaust stack for products of combustion
- Ash collection and removal
- Controls and monitoring system (a desired option would be off-site and real-time monitoring of performance parameters by the equipment supplier)

3.2.7. Heat Delivery and Distribution

The challenge: how to evenly distribute hot air (e.g., 160°F.) from a single point source (i.e., a duct from the furnace) throughout a barn that is 40’ x 400’ (or 40’ x 200’ during half-house brooding), recognizing that the heat must be distributed down low and evenly across the floor (in both dimensions) but without excessive velocity or temperature that would be detrimental to the birds (particularly young chicks). Such hot air distribution must also occur whether the house conditions are static or during a ventilation event (when the entire volume of air within the barn is exhausted within one minute).

Several methods of in-house thermal energy distribution were considered (some of which have been tried by others but were not commercially successful):

- Use of water as a medium: The water would be heated using an air-to-water heat exchanger within the furnace system, and hot water radiators or heat exchangers within the house. These systems typically failed because the heat exchangers inside the broiler house would plug up (due to the extremely dusty conditions), resulting in an almost total loss of thermal transfer capacity. Systems using steam cycles were considered impractical for on-farm applications, given the complexities of operating and maintaining a small-scale steam-based system.
- Use of outside ducts: The hot air would leave the furnace and enter a manifold located on the outside of the house and running the length of the house (whether on the side or the roof). However, this option was eliminated for logistical and cost reasons.
- Use of rigid metal ducts installed in the peak of the house ceiling: This option was attractive because the units could also serve as fresh air inlets during non-heating periods, but was rejected because of high capital cost and the considerable effort required to keep the units reasonably free of dust.
- Use of inflatable plastic tubes: This option was used in both house 3 (for the pellet-fired system) and house 1 (for the sawdust-/litter-fired system). These tubes are desirable because the equipment is readily available, entails low capital cost, is easily installed, has low operating cost, and has already used within the agricultural sector, and proven for this application.[21] In addition, the units provide an acceptable method of distributing the hot air both linearly down the long axis of the barn and across the cross-section of the barn, given the location of the exit holes in the material.

  Two tubes are used for each house (one for each half, allowing only one to be used during half-house brooding). The plastic tubes are inflated by an axial fan positioned at the intake end of each tube. The tubes have 3" outlet holes positioned every 2 feet at approximately 120° and 240° from a cross-sectional perspective. This design provides for gentle recirculation of the air within the barn (from the exit holes back to the fan intake). The hot air from the furnace is dumped into the open air inside the house (and near the ceiling) at least several feet away from the axial fans. This enables the hot air from the furnace to be effectively mixed with the air inside the barn (including the re-circulated air from the tube system) prior to entering the tubes, so that air temperatures are below the manufacturer's rated maximum tolerance level.

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[21] Inflatable plastic tubes had been successfully used for a previous wood pellet-fired poultry house furnace demonstration project administered by Winrock International during 1995~1997).

Figures 40 and 41 depict cross-sectional and plan-view graphics, respectively, of a 30" diameter Jet Tube within a 40' wide broiler house. Figures 42 and 43 show the units installed and operating.

Figure 40: Cross-sectional schematic of a plastic tube hot air distribution system

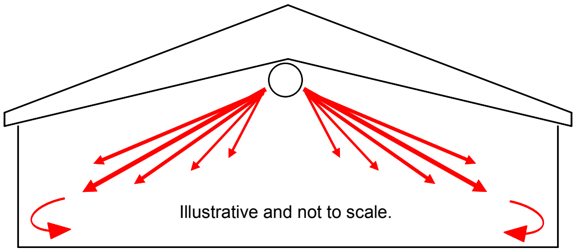

Figure 41: Plan-view schematic of a plastic tube hot air distribution system

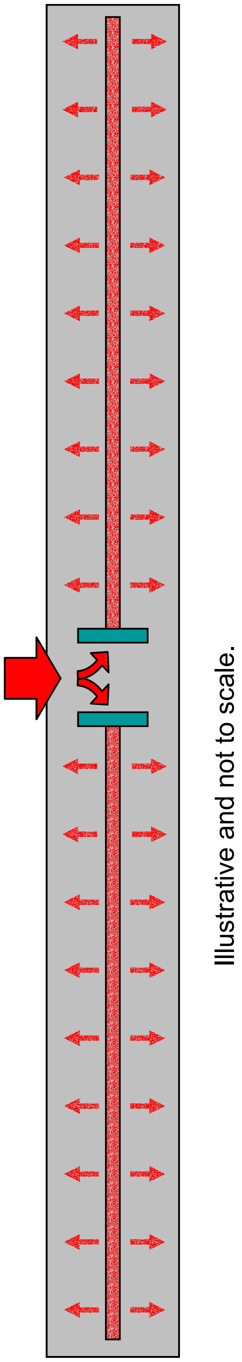

Figure 42: Plastic tube hot air distribution system used at the UA facility

Figure 43: Axial fan that inflates the hot air distribution tube

3.2.8. Ash Management

Removal of hot ash and subsequent storage of the material is an essential component of a furnace system, particularly for a litter-fired system. As shown in Table 3, the weight and volume of ash produced varies by feedstock.

Table 3: Ash production calculations

	wood pellets	broiler litter	low-grade sawdust	
total biomass fuel required	34	66	66	tons / year
weight of ash produced	1%	20%	5%	by weight
weight of ash produced	14	552	138	pounds / day
weight of ash produced	0.3	13.2	3.3	tons / year
bulk density of ash	40	40	40	pounds / cubic foot
volume of ash produced	0.4	13.8	3.5	cubic feet / day
volume of ash produced	17	661	165	cubic feet / year
volume of ash produced	0.6	24.5	6.1	cubic yards / year

As evident from Table 3, the quantity of litter-derived ash that would be generated and managed is substantially greater than sawdust-derived ash or wood pellet-derived ash (premium pellets have less than 0.5% ash by weight). However, unlike ash from the other two materials, litter-derived ash has considerable economic value as an inorganic fertilizer, consisting of all of the minerals (e.g., phosphorus, potassium, and calcium) and trace elements contained in the broiler litter. In fact, capture of all of these constituents – including, in particular, the phosphorus – makes litter-to-energy systems extremely attractive to growers and integrators located/operating in areas of concentrated production such as Northwest Arkansas…provided that the litter-derived ash is captured and, where necessary, exported from the production farm (and, in some cases, even out of the watershed). Thus, deployment of litter-fired furnaces in a region of concentrated poultry production should include a plan for subsequent aggregation and management (including, if necessary, export) of the furnace ash.

One of the original objectives of this project was to analyze the biomass-derived ash, particularly the litter-derived ash, to ascertain its constituents, including those of potential concern from environmental and/or agronomic perspectives (including, in particular, arsenic[22]). Such analyses could not be performed since an operational litter-fired system was not successfully developed.

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[22] An analysis of data obtained through the Internet concluded that the amount of elemental arsenic in 100,000 tons of broiler litter is roughly 6,000 pounds – about the same amount of elemental arsenic contained in the treated lumber used to construct about 1,300 typical residential decks.

3.3. Environmental Considerations

Deployment of biomass energy systems could have two significant environmental benefits:

- Displacement of fossil fuels by renewable fuels (e.g., displacement of propane by sawdust). For example, if half of the existing broiler houses were retrofitted with bioenergy systems, approximately 325,000,000 gallons of propane would be displaced.
- Mitigation of nonpoint source water quality concerns associated with land application by export of the surplus material (and the surplus phosphorus contained therein) – this benefit would apply only to litter-fired energy systems.
- Reduction in greenhouse gases – by using sawdust as fuel, the carbon is converted into carbon dioxide rather than methane (resulting from degradation of accumulated and unused sawdust).

However, there are also several concerns regarding emissions & ash that need to be addressed. Concerns are focused primarily on the fate of certain constituents through the system (whether exhausted through the stack or captured in the ash):

- Regarding carbon: Furnace development efforts were driven in large part by monitoring carbon monoxide (CO) as measurement of system performance (i.e., minimal output of CO in the stack indicates efficient system operation, with the carbon being converted into carbon dioxide instead).
- Regarding nitrogen: It is assumed that all nitrogen would be volatilized and exit the system through the stack as NOx; detailed data regarding the form and quantity of NOx is needed to ensure that the systems will meet applicable state/federal regulatory requirements (if any, given the relatively small scale of the on-farm energy systems).
- Regarding phosphorus: As noted previously all of the phosphorus contained in poultry litter would be captured in the litter-derived ash, thereby converting a potential problem into a potential asset.
- Regarding sulfur: It is assumed that most of the sulfur contained in poultry litter would be captured in the litter-derived ash, with the remainder emitted from the stack; data is needed to determine if stack emission levels of sulfur are within acceptable limits.
- Regarding arsenic: Historically, arsenic has been added as a feed ingredient (e.g., in the form of Roxarsone), primarily as a poultry growth stimulator; however, in recent times, use of arsenic has been reduced or even eliminated by some integrators. Additional data is needed regarding the fate of this element through a litter-to-energy system (it is assumed that all of the element would pass through the system and end up in the ash). Although some air emissions monitoring occurred during furnace development (particularly CO and CO2), none of the units were sufficiently developed under this project to obtain reliable data reflective of commercial operations.

3.4. Deployment Considerations

3.4.1. Regional Coordination

Given the nature of the poultry industry, vendors should identify and target specific areas of concentrated poultry production for product sales; this would also define specific territories for after-sales support. It is recommended that vendors target all growers within a specific area, regardless of integrator affiliation.[23]

Aggregation and subsequent export of ash from litter-fired furnaces should be coordinated on a regional basis. This will likely require clarification of ownership of and responsibility for management of the ash material. Ownership of the ash and responsibility for its export by the vendor would greatly increase the attractiveness of litter-fired systems to both growers and integrators (because of the transfer of potential liability associated with the phosphorus-rich material from growers/integrators to a third party).

3.4.2. Target Customers

Purchasers of the on-farm bioenergy systems would be poultry growers (i.e., *not* the integrators). More specifically, the target customers should be:

- Growers with reasonable access to a source of pellets (for pellet-fired systems).
- Growers with reasonable access to sawdust (for sawdust-fired systems).
- Growers that are not actively using their litter for agronomic purposes (for litter-fired systems).
- Growers in watersheds that need to export surplus litter (for litter-fired systems).
- Growers seeking an alternative for mortality management (for either litter- or sawdust-fired systems).
- Growers with existing houses (i.e., retrofit systems) vs. new construction.

3.4.3. Sales Strategies

There are three primary options for selling on-farm bioenergy systems:

- Direct sales to growers by the furnace manufacturer – theoretically an attractive option, but would require the manufacturer to establish a local presence and develop in-depth knowledge of and contacts within the poultry industry

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[23] Although, in some cases, it may be desirable to target integrator-specific growers, if deployment of the furnaces in that area is backed by a specific integrator.

- Sales through local poultry equipment supply companies – this option is attractive, given the existing companies' knowledge of and close working relationships with both growers and integrators, but could introduce a significant middle-man cost.
- Lease programs – working with a financing entity such as a local bank, this option could be particularly attractive to growers, but would still require local knowledge by the sales team (whether the manufacturer's or a local supply company's).

A few other points regarding sales strategies:

- In the event of sales of furnaces (i.e., not leasing), the vendor could work with a financing enterprise to be able to offer financing arrangements to purchasers (which would presumably enhance the vendor's ability to sell furnace units).
- Vendors should consider requiring credit insurance for each purchase that is leased or financed, as a hedge against the risk that the grower will go out of business or lose his contract with his integrator prior to the end of the financing period.
- Vendors should try to obtain financing guarantees and/or other financial support for deployment and/or operations from integrators for deployment of furnaces on their growers' farms. This would be particularly true for deployment of litter-fired systems in watersheds where there are surplus litter concerns, since the litter-to-energy systems could greatly reduce the integrator's potential environmental liabilities associated with surplus nutrient management (primarily through capture and subsequent export of the surplus phosphorus).

3.4.4. After-Sales Support

After-sales support of the furnace systems must, of course, be a component of a vendor's business and product deployment plan. Several factors to consider include:

- Product warranties: What would be the scope and duration of the warranty(s)? Would there be different warranty options? What warranty(s) would be included (if any) in the price of the furnace? How would warranty options be priced?
- Operational support: What support would the manufacturer/vendor/agent provide (e.g., an operating manual, initial on-site instruction, on-line technical support, or phone-based technical support)? Where would such support be based, who would provide it, and how would the technical support staff be trained?
- Product servicing: Who would perform routine on-site servicing and/or major maintenance? Where would they be located, what would be their training, and how might a quality control or quality assurance program be established? Service logistics must

also be addressed, e.g., need for a service truck(s), locally available spare parts, and availability of additional parts required for major maintenance.

3.4.5. Feedstocks Supply Risks

From a furnace purchaser's perspective, assurances are desired regarding access to feedstocks when a furnace system is purchased, at least for the payoff period of the system. For pellets, this could be a long-term purchase contract with the pellet manufacturer. For sawdust, this could be a long-term agreement with a nearby sawmill. But for litter, the situation is different and the risk is considerably higher. Even though growers would use their own litter as fuel for a litter-fired furnace system, production of the litter is dependent on production of birds, and broiler producers typically have only flock-to-flock production contracts with their integrators.[24] Thus, such lack of long-term production agreements between growers and integrators equates to high financial risk regarding purchase of a litter-fired heating system (or any other production facility equipment upgrade).

One method of addressing this risk is through insurance – e.g., the vendor could require the grower to purchase credit insurance that would pay off the balance owed to the vendor in the event [for whatever reason] the grower's production is disrupted or terminated. Another option might be purchase of similar insurance by the vendor, with the cost of said insurance incorporated into the sales or lease price of the furnace system.

3.4.6. Industry Coordination

Furnaces can be sold to growers only if their respective integrators approve of the technology…thus, it is essential that furnace vendors be able to convince integrators of the worthiness of their product. For this to happen, vendors must be able to demonstrate a comprehensive understanding of the industry and be able to demonstrate the viability and feasibility of their bioenergy systems.

In addition, vendors for litter-fired systems must be able to essentially guarantee that any litter-derived phosphorus will be aggregated and effectively managed (including, where necessary, export of the phosphorus-rich ash from the farms within an area of concentrated poultry production that use the furnaces). As noted previously, the ability to capture and remove the surplus litter/phosphorus (in the form of ash) from production farms located within certain watersheds is a major potential benefit for the poultry industry and a major potential selling point for the furnace vendor.

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[24] Some growers have a one-year contract (e.g., about 6 flocks), which still constitutes risk vis-à-vis long-term litter supplies.

Use of a third-party enterprise may be a desirable option for ash aggregation and management. One option may be the Ozark Litter Bank (OLB), a nonprofit organization that may be established to assist with surplus litter management in the Ozark Highlands Plateau region. For more information regarding the OLB, refer to www.organix.org/publications or contact Dr. H. L. Goodwin, Poultry Economist at the University of Arkansas.

3.5. Economic Considerations

3.5.1. Methodology and Assumptions

Furnace-specific economic analyses and projections could not be undertaken since no furnace units were developed to commercialization (or even pre-commercialization) status. Nonetheless, several basic economic analyses were performed that provide some insights into and guidance for potential deployment of on-farm bioenergy systems. The economic analyses set forth in this section entail estimates *on a per-house basis* of:

- Basic economic and financial assumptions
- Annual revenues / benefits (and the associated net present value of these benefits)
- Annual operating expenses (and the associated net present value of these expenses)
- Capital costs
- Feasibility analyses, essentially consisting of a comparison of the net present value of the estimated annual revenues/benefits and operating expenses vs. capital costs
- Break-even/sensitivity analyses based on key variables

A service life for the furnace system of 10 years has been assumed and used for net present value calculations. Note that, as a result of numerous discussions with industry representatives (both growers and integrator staff), it was determined that a maximum simple payback period for a complete on-farm bioenergy system of five to six years would be considered acceptable.

Another key economic assumption is the price of propane, since (as noted in section 3.2.2) the target level of propane displacement by the bioenergy systems is eighty-five percent. It is important to note that the poultry industry often enjoys lower-than-market propane prices, often due to large-volume advance purchases of propane by integrators.[25] During the nineties, the typical delivered price of propane paid by poultry growers in the Ozark Highlands Plateau region has been about $0.65 per gallon, even when retail prices in the same region were $1.00 per gallon or more.[26] Average prices paid by poultry growers in the project region have risen slightly and are currently assumed to be $0.75 per gallon.

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[25] Some integrators have even established gas supply companies, both as a means of acquiring fuel at low cost and for ensuring supplies of the fuel to their growers (thereby minimizing risks of production disruptions due to fuel outages during supply shortages that typically occur during mid-winter periods entailing maximum heating demand).

[26] Although prices temporarily rose to >$1.00 during some heavy-demand periods (e.g., during the Winter of 2000~2001).

Numerous factors affect the prices of propane in different regions of the country, and in recent years the cost of propane to poultry growers has varied considerably and has tended to increase over time.[27] For example, the price of propane in the region jumped considerably during the 2000~2001 heating season due to supply shortages and high demand, and it is widely anticipated that future prices of propane will increase. Thus, section 3.5.6 contains several sensitivity analyses primarily based on variations in propane prices.

3.5.2. Revenues / Benefits

The primary economic benefit of an on-farm furnace is the value of the displaced propane. While this is not a revenue *per se*, the cost savings can be considered as such.

Another economic benefit (and potentially a true revenue) is the value of the ash derived from litter-fired furnaces (assuming that the nutrient-rich ash material is aggregated and subsequently sold as an inorganic fertilizer). Whether revenues from sale of the ash are received directly by the grower or, more likely, by a third-party engaged in ash aggregation and management, the proceeds from sale of the ash can be assumed to positively affect the overall economics of deploying an on-farm litter-fired bioenergy system. Note that the assumed value of litter-derived ash is $40~$50 per ton of ash (FOB plant), based on estimates developed for large-scale off-farm litter-to-energy facilities. This value is also used for valuing the ash generated by on-farm litter-to-energy systems (assuming that the quality of ash generated by such systems is similar, from an inorganic fertilizer material perspective). However, the net value from sales of farm-derived ash must be discounted to reflect the cost of aggregating the ash from the farms to a central point for subsequent sales.

Other possible economic revenues or benefits could be supplemental financial assistance for deployment or operation of bioenergy systems. There are two basic sources for such possible supplemental financial assistance: the public sector and/or the integrators.

There are several federal/state programs that could potentially be of assistance:

- The Environmental Quality Incentive Program (EQIP), administered by the U.S. Department of Agriculture's (USDA) Natural Resources Conservation Service agency. Various applicable activities are potentially eligible for financial support through

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[27] Growers typically fill up their propane tanks during the summer when prices are relatively low; however, this is not a complete hedging strategy, since most farms have two 1,000-gallon propane tanks per house whereas average propane consumption is 5,000 gallons per house per year – meaning that the tanks will have to be filled at least 1.5 times during winter periods when propane prices are relatively high.

EQIP[28] such as construction of litter stacking sheds and export of surplus litter/phosphorus from the farm.[29]

- The Nonpoint Source Program (NPS) from the U.S. Environmental Protection Agency (EPA). NPS funds are usually administered through each state's soil and water conservation agency or equivalent and are generally used for watershed-level activities, although the financial support can indirectly benefit participating farms (e.g., through financial assistance for a regional surplus litter management initiative that could conceivably cover the cost of aggregating and exporting ash from on-farm litter-to-energy systems, or perhaps even supporting the deployment of such energy systems as means of reducing potential water quality impacts by avoiding land application of the litter used on-farm as fuel).
- Deployment of on-farm renewable energy systems though funding programs established by the 2002 Farm Bill and administered by USDA and the U.S. Department of Energy (DOE). These assistance programs could potentially support pellet- or sawdust-fired systems as well as litter-fired systems.
- Loan guarantees from USDA or state agricultural/economic development agencies could support deployment of on-farm furnace systems by reducing financial risks for the buyers (and the sellers) of the equipment.
- Several state-level programs that have been established in various regions of the country that provide financial support for renewable energy and/or surplus litter management may be available to assist with deployment of on-farm furnace systems.

Regarding possible financial support from integrators for deployment/operation of on-farm bioenergy systems:

- Some integrators already provide financial assistance to growers for energy expenses (e.g., through reimbursement or supplement energy payments to offset excessive propane expenses during periods of high demand/high prices, or through subsidized propane prices), so financial support of bioenergy systems could simply entail internal adjustments in an integrator's existing support programs.
- In areas of concern regarding possible water quality impacts from traditional land application of litter, integrators may wish to provide financial support to growers who use on-farm litter-to-energy systems (with subsequent export of the nutrient-rich ash co-product) as a means of addressing such concerns (and reducing potential liability associated with litter management on the part of both the integrators and the growers.

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[28] Authorized practices and eligibility under EQIP varies from state to state.

[29] EQIP support would likely be limited to farms using litter-fired furnaces.

It is certainly conceivable that some supplemental financial assistance could be a combination of assistance from both public and private sources. Some basic economic assumptions and calculations regarding potential revenues/benefits are set forth in Table 4. Note that the base case analyses shown in Table 4 reflect zero supplemental financial assistance (from either public or private sources).

Table 4: Basic economic assumptions and calculations re potential revenues/benefits

	wood pellets	broiler litter	low-grade sawdust	
typical current fuel consumption - propane	5,000	5,000	5,000	gallons / year
target displacement level (biomass vs propane)	85%	85%	85%	
quantity of propane to be displaced	4,250	4,250	4,250	gallons / year
average cost of propane	$0.75	$0.75	$0.75	per gallon
value of displaced propane	$3,188	$3,188	$3,188	per year
amount of ash produced (from Table 3)	0.3	13.2	3.3	tons / year
potential value of the ash, FOB aggregated	$0.00	$40.00	$0.00	per ton
less estimated aggregation/disposal cost	$8.00	$21.00	$8.00	per ton
net value of ash	-$8.00	$19.00	-$8.00	per ton
net value of ash	-$2.75	$251.16	-$26.44	per year
amount of supplemental financial assistance	$0	$0	$0	per year
total value of displaced propane + ash	$3,185	$3,439	$3,161	per year
net present value (@ 10 years, 7% APR)	$22,368	$24,152	$22,202	

3.5.3. *System Operating Expenses*

The estimated operating expenses noted below and the net present (negative) value of those expenses are shown in Table 5.

- Cost of the biomass fuel (i.e., the price paid to the fuel source)
- Delivery cost (i.e., estimated transportation cost; for pellets this represents the cost of a contracted grain truck for transport from the pellet mill to the farm; for litter, this represents the cost of using the farm's front-end loader for transport from the stacking shed to the fuel bunker/storage container[30]; for sawdust, this represents the cost of a contracted dump truck for transport from the sawmill to the farm)
- Maintenance expenses (i.e., for all components of the system)
- Other expenses (e.g., credit insurance, liability insurance, etc)

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[30] It is assumed that the cost of clean-out and delivery of the litter into the stacking shed is a component of existing farm operations and not associated with the on-farm litter-to-energy system.

Table 5: Basic economic assumptions and calculations re annual operating expenses

	wood pellets	broiler litter	low-grade sawdust	
total biomass fuel required (from Table 2)	34	66	66	tons / year
cost of biofuel from source	$85.00	$0.00	$0.00	per ton
delivery cost for biofuel	$20.00	$3.00	$10.00	per ton
total annual expense for biofuel	$3,615	$198	$661	per year
estimated maintenance expenses	$200.00	$500.00	$350.00	per year
other expenses (insurance, etc)	$500.00	$500.00	$500.00	per year
total annual expenses	$4,315	$1,198	$1,511	per year
net present value (@ 10 years, 7% APR)	-$30,307	-$8,416	-$10,612	

3.5.4. System Capital Costs

The estimated capital costs for each of the primary system components and total system cost are shown in Table 6. Note that these costs are only rough estimates, as no detailed information was available or determined for the specific furnace systems pursued under this project. Also note that the costs for primary fuel storage are not considered part of the bioenergy system cost.

Table 6: Estimated capital costs

	wood pellets	broiler litter	low-grade sawdust	
fuel bulk storage	n/a	existing stacking shed	at sawmill	
near-furnace fuel storage & handling	$2,500	$3,000	$3,000	per year
furnace system	$7,000	$10,000	$8,500	per year
hot air distribution component	$2,500	$2,500	$2,500	per year
ash storage component	$500	$1,500	$800	per year
total estimated capital cost	$12,500	$17,000	$14,800	per year

3.5.5. Overall Feasibility

As shown in Table 7, the overall feasibility of each of the three furnace systems was determined by simply comparing the net present value of the annual revenues/benefits less the net present (negative) value of the annual operating expenses to the estimated capital cost. The net result is that none of the systems are considered feasible under current conditions and/or the assumptions set forth herein (although the litter-fired system is close).

Table 7: Overall feasibility calculations

	wood pellets	broiler litter	low-grade sawdust
NPV of estimated benefits / revenues (Table 4)	$22,368	$24,152	$22,202
NPV of estimated annual expenses (Table 5)	($30,307)	($8,416)	($10,612)
NPV of estimated benefits less expenses	($7,939)	$15,735	$11,590
total estimated capital cost (Table 6)	($12,500)	($17,000)	($14,800)
summary net benefit (deficit)	($20,439)	($1,265)	($3,210)
result	not feasible under current conditions / assumptions	not feasible under current conditions / assumptions	not feasible under current conditions / assumptions

3.5.6. Break-even Analyses

A series of analyses were performed to determine the price of propane at which the economics for each furnace system would break even. The analyses were performed across two variables:[31]

- External financial support (at $0, $250, and $500 per house per year levels)
- Propane displacement levels (at 80%, 85%, and 90% levels)

The $0 external financial support and 85% displacement levels are the base case assumptions previously noted. The external financial support levels of $250 and $500 per house are equivalent to subsidies of about $2.50 and $5.00 per ton of litter, respectively. The results of these analyses are set forth in Table 8 and shown graphically in Figure 44.

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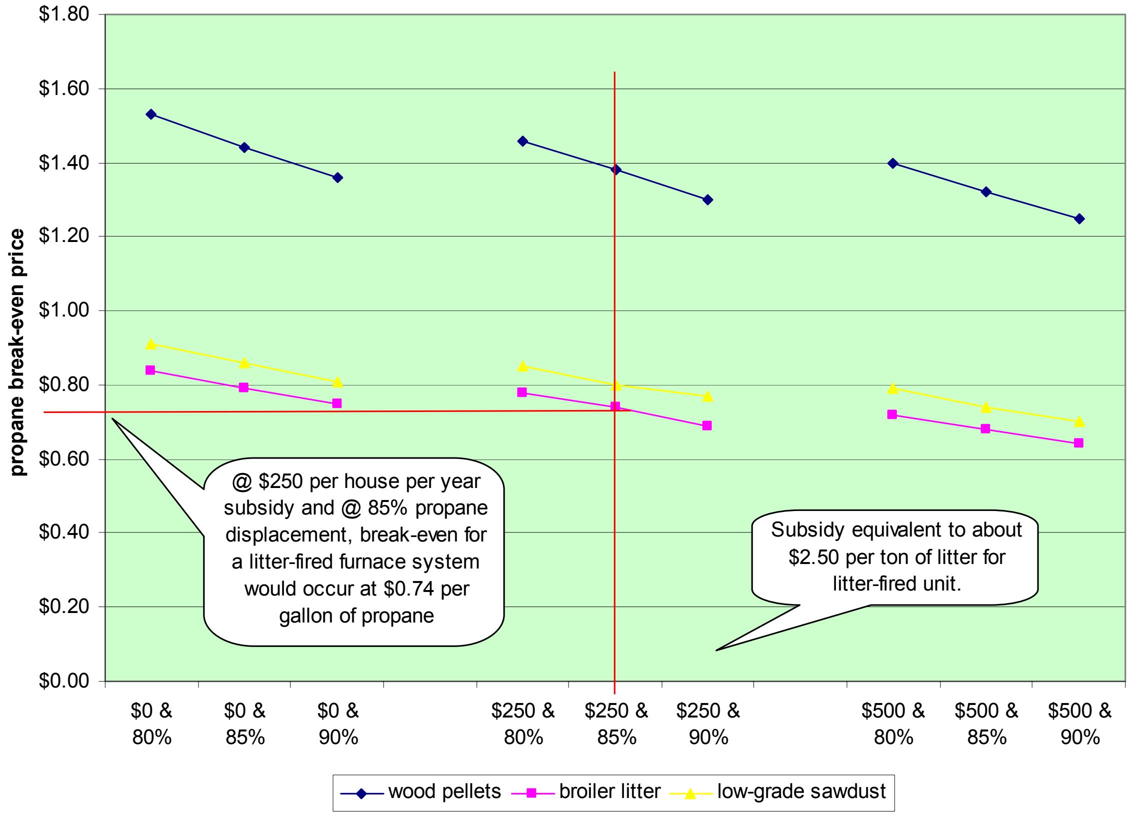
[31] The calculations assume that all other assumptions are constant, including, for example, the cost per ton for delivery of the fuel to the farm (i.e., that transportation energy costs remain constant as propane prices rise).

Table 8: Prices of propane that would result in economic break-even

projected price of propane for break-even	wood pellets	broiler litter	low-grade sawdust	
with $0 /house /yr external financial support	$1.44	$0.79	$0.86	/ gallon
with $250 /house /yr external financial support	$1.38	$0.74	$0.80	/ gallon
with $500 /house /yr external financial support	$1.32	$0.68	$0.74	/ gallon
with $0/yr subsidy & 80% propane displacement	$1.53	$0.84	$0.91	/ gallon
with $0/yr subsidy & 90% propane displacement	$1.36	$0.75	$0.81	/ gallon
with $250/yr subsidy & 80% displacement	$1.46	$0.78	$0.85	/ gallon
with $250/yr subsidy & 90% displacement	$1.30	$0.69	$0.77	/ gallon
with $500/yr subsidy & 80% displacement	$1.40	$0.72	$0.79	/ gallon
with $500/yr subsidy & 90% displacement	$1.25	$0.64	$0.70	/ gallon

Figure 44: Prices of propane that would result in economic break-even



@ $250 per house per year subsidy and @ 85% propane displacement, break-even for a litter-fired furnace system would occur at $0.74 per gallon of propane

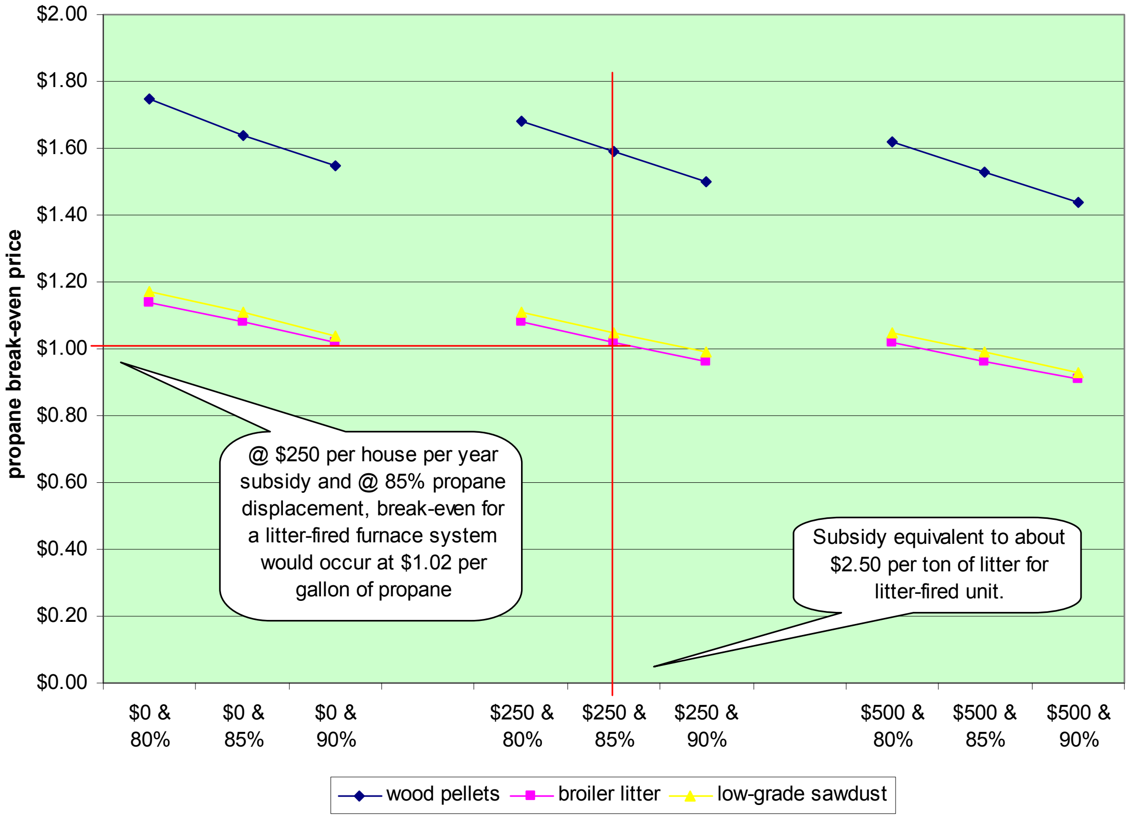
Subsidy equivalent to about $2.50 per ton of litter for litter-fired unit.

Table 9 and Figure 45 depict the same results, but with an assumption that the total capital cost of each furnace system is 150% of that shown in Table 6.

Table 9: Prices of propane that would result in economic break-even but at 150% of estimated capital cost

projected price of propane for break-even	wood pellets	broiler litter	low-grade sawdust	
150% of estimated system capital cost	$12,500	$17,000	$14,800	
with $0 /house /yr external financial support	$1.64	$1.08	$1.11	/ gallon
with $250 /house /yr external financial support	$1.59	$1.02	$1.05	/ gallon
with $500 /house /yr external financial support	$1.53	$0.96	$0.99	/ gallon
with $0/yr subsidy & 80% propane displacement	$1.75	$1.14	$1.17	/ gallon
with $0/yr subsidy & 90% propane displacement	$1.55	$1.02	$1.04	/ gallon
with $250/yr subsidy & 80% displacement	$1.68	$1.08	$1.11	/ gallon
with $250/yr subsidy & 90% displacement	$1.50	$0.96	$0.99	/ gallon
with $500/yr subsidy & 80% displacement	$1.62	$1.02	$1.05	/ gallon
with $500/yr subsidy & 90% displacement	$1.44	$0.91	$0.93	/ gallon

Figure 45: Prices of propane that would result in economic break-even but at 150% of estimated capital cost



3.6. Other Efforts Underway Re On-Farm Systems for Heating Broiler Houses

In light of the significant potential opportunities for sales of on-farm bioenergy systems—particularly litter-fired—several companies are currently pursuing (or intend to pursue) farm-scale energy systems for heating poultry houses. In some instances, cogeneration (thermal and electrical energy outputs) is envisioned. A brief description of some of these efforts follows.

- **Community Power Corporation** (CPC). CPC is based in Littleton, Colorado, and has been working on small bioenergy systems since 1995, with much of their product development efforts supported by the DOE's Small Modular Biomass program, administered through the National Renewable Laboratory in Golden, CO. CPC began installing commercial gasification units worldwide in 2001, primarily focused on small-scale electricity production for off-grid applications.

  Also in 2001, CPC (with support through DOE's Small Business Innovative Research [SBIR] program) began investigating the possibility of adapting their gasification technology to use broiler litter for thermal/electrical output. Based on the results of the Phase 1 assessment, CPC began an SBIR Phase 2-funded project in 2002 to develop and test a full-scale prototype system. With assistance from the Foundation for Organic Resources Management and the University of Arkansas, CPC established an Industry Advisory Group to help guide their development efforts. It is anticipated that CPC's first litter-fired farm-scale gasification system will be tested at the UA's BERF during the 2003~2004 winter. The initial system will be for one house, although commercial units will be 2-house and 4-house units.

- **Advance Biomass Carbons** (ABC). Located in Owensville, Missouri, ABC has been developing a 2-house litter-fired combustion system for over two years. Public demonstrations of the prototype are scheduled to begin in 2003.

- **Alternative Energy Solutions** (AES). Based in Fort Mill, South Carolina, AES is developing both on-farm and off-farm litter-to-energy systems. The company's principals were previously with Renewable Energy Corporation.

- **Lynndale Wood Heating System** (LWH). Based in Harrison, Arkansas, LWH has been making cordwood-fired furnaces for residential and light commercial applications since 1974. In 2002 the company announced its intent to develop a litter-fired furnace system for heating poultry houses.

4. Summary Observations & Conclusions

4.1. Summary Observations

- There are about 130,000 broiler farms in the United States, of which about 20,000 are located in the Ozark Highlands Plateau region.

- The need for more cost-effective space heating systems for broiler farms is great…fuel for space heating is the single highest operating expense for broiler producers.

- Most broiler farms use liquefied petroleum gas as fuel—mostly propane, although some butane is used; the remaining growers primarily use natural gas. Only a few systems use coal- or cord-wood-fired heating systems.

- A typical broiler farm in the Ozark Highlands Plateau region uses about 5,000 gallons of propane per house per year. In the past ten years prices paid by the region's growers averaged about $0.65 per gallon, although prices have varied considerably, depending on seasonal demand vs. supplies – during the winter of 2000~2001 many growers could not get propane for less than $1.00 per gallon. Average prices have risen slightly; the current average price is estimated to be $0.75 per gallon (as of June 2003).

- Most growers in the Ozark Highlands Plateau region (and in many other areas of concentrated poultry production in the southeastern United States, where over 75% of poultry production in the United States is located) are located near sources of surplus sawdust, which could be obtained by the growers for the cost of delivery (estimated at $10 per ton). Low-grade sawdust is typically 50% water, with an energy content of about 4,600 Btu per pound *as is* and an ash content of about 5%.

- There are increasing pressures for many growers in the Ozark Highlands Plateau region (and in many other areas of concentrated poultry production in the United States) to embrace alternative management practices for at least some of their litter. Litter has been successfully used as a fuel for large-scale off-farm energy facilities and therefore could (at least in theory) be used as a fuel for small-scale on-farm energy systems.

- Numerous factors affect the quantity, nature, and properties of broiler litter. On average, about 130 tons of litter per year is produced in a typical broiler house located in the Ozark Highlands Plateau region that produces an average of six flocks per year. Of this amount, 30 tons is removed as cake at 6 tons per de-caking between flocks, with the remaining 100 tons removed at the end of the year. However, in recent years many growers have begun shifting to total clean-out every two years or more.

- The energy content of broiler litter produced in the region is about 4,600 Btu per pound *as is*, based on a typical moisture content of 25% and a typical ash content of 20%.

- A farm-scale litter-fired or sawdust-fired heating system could—at least in theory—reduce a grower's operating expenses while providing management options for surplus biomass.

- Given the large number of broiler houses in the region and elsewhere in the U.S., sales of such furnaces would be an attractive business opportunity. Additional markets for such furnace systems might include turkey houses, other farm buildings, rural shops, and other light commercial/industrial facilities with access to the biomass feedstocks.

- To be successful, the furnace system would have to satisfy three criteria:
  - Technical viability – The furnace system must be functional, reliable, and robust, and able to withstand operating conditions encountered on broiler farms.
  - Economic feasibility – The furnace system must be affordable by the consumer (i.e., the poultry grower) and represent a positive return on investment; supplemental financial assistance may be available from public and/or private sources to offset the cost of such on-farm bioenergy systems (assuming that the systems satisfy the other two criteria).
  - User friendliness – The furnace system must be readily usable by the broiler farm operator under typical farm conditions…i.e., the unit should require very little attention, management, or technical expertise, and must not interfere with broiler production efforts.

- In addition to meeting the foregoing requirements, the challenges of developing a commercially viable farm-scale biomass energy system are not to be underestimated:
  - The poultry industry is considered to be conservative and risk-averse, in large part because competition within the industry is keen, profit margins are thin, and potential liabilities associated with production system failures are large.
  - Broiler houses have high and variable heating requirements.
  - The poultry industry has a high comfort level with existing gas-fired heating systems:
    - Broiler chicks are perceived to prefer existing radiant brooder heaters rather than forced-air heating systems (sometimes this is referred to as the "mothering effect").
    - Existing gas-fired heating units have proven convenience, reliability, & low cost.
    - Existing equipment suppliers are close to (and often inside) the poultry industry and are well-established.

- The objectives of this project were to:
    - Scale up an existing prototype small-scale green sawdust-fueled heating system and adapt it for use in heating poultry houses.
    - Adapt the same system to use poultry litter as fuel.
    - Scale up an existing pellet-fired residential heating system and adapt it for use in heating poultry houses.
    - Demonstrate and evaluate the technical and economic feasibility of the systems on a full-scale calibrated poultry house facility and other field sites.
    - Work with the equipment manufacturer(s), the poultry industry, and other organizations to commercialize the technology.
- Primary project partners included:
    - Arkansas Energy Office (the prime grant recipient).
    - Foundation for Organic Resources Management (the project coordinator).
    - Northern Light R&D (the original designer of the raw material-fired furnace).
    - Pyro Industries (the original for-profit product developer).
    - External Power & Wood-Mizer Products (the subsequent for-profit product developers).
    - University of Arkansas (system performance analyses and demonstrations).
- Four prototype farm-scale biomass-fired furnace systems were developed and tested under this project since 1997; funding support was provided by the U.S. Department of Energy through its Commercialization Ventures Program. The four systems included:
    - A pellet-fired system developed by Pyro Industries.
    - An unprocessed biomass-fired system designed by Larry Dobson (Northern Light R&D).
    - Two unprocessed biomass-fired systems developed by External Power in conjunction with Wood-Mizer (based on the Dobson design).
- For a variety of reasons, none of the efforts under this project were successful in terms of commercializing and marketing a biomass-fired furnace for heating poultry houses. In fact, with regard to the three commercialization criteria set forth above, none of the systems were able to satisfy the first criterion (technical feasibility). However, as noted in this report and summarized below, considerable information was compiled and numerous lessons were learned that should be of benefit to others that are pursuing (or considering pursuit of) such systems.

- Broiler houses:
  - The typical older house in this region is 40’ by 400’, with a capacity of about 20,000 birds per flock.
  - Newer houses tend to be somewhat larger—often 42’ by 500’, with capacities of 25,000 ~ 28,000 birds, depending on the size of birds at harvest.
  - Ideally, the houses are aligned in parallel, with 50’ to 75’ spacing between the houses; in reality, the alignment / spacing / orientation of the houses varies, affected by the farm’s topography and other factors.
  - Older houses were typically constructed with open sidewalls covered with plastic drop curtains that are dropped in hot weather for cross-flow ventilation; in cold weather the curtains are opened slightly at the top along one wide, with exhaust of ammonia/dust generated within the house provided by fans on the opposite side.
  - Stirring fans are also used in many houses to facilitate ventilation.
  - Newer houses are usually designed and constructed using the tunnel ventilation design, consisting of solid side walls with exhaust fans located at one end of the building with fresh air intakes at the other end or near the ends of the side walls at the ends opposite the fans.
  - Conventional 40’ x 400’ houses typically employ eight 48” exhaust fans (@ 20,000 cfm per unit, resulting in a complete air exchange within the house each minute.
  - Larger houses usually have increased fan capacity, e.g., 10 48” fans, resulting in a complete air exchange within the house in less than one minute.
  - The fans operate intermittently; the timers are usually established by the farm operator/manager, based on perceived conditions; in some instances, the operator can also set the exhaust fans to respond to in-house thermostats.
  - Tunnel ventilation systems are more effective and efficient than are drop-curtain designs in exhausting dust/ammonia and providing fresh air to the birds, but these designs greatly increase producers’ reliance on electric power.
  - Houses employ both open truss and drop ceilings, supported by wood or metal ceiling trusses (refer to Figures 21 and 22).
  - The 4” ~ 6” layer of litter serves as an excellent insulator between the birds and the earthen floor; newer houses have more ceiling insulation

- Conventional gas-fired heating systems:
  - Almost all broiler houses are currently being heated with gas-fired appliances, mostly LPG (primarily propane, although some use butane).
  - There are two primary types of gas-fired heaters used: brooders and forced-air heaters; most houses use both types, although some use only brooders.
  - Like all other equipment inside a broiler house (e.g., watering lines, feed lines), the heaters are suspended from the ceiling on thin wire so that the units can be raised up during bird harvesting and between-flock maintenance, including litter clean-out.
  - The brooders or pancake heaters are radiant-type heating units suspended to within 2~3 feet of the floor; a typical pancake brooder is rated at 30,000 Btu.
  - The brooders are considered particularly effective during the first few days after chicks are placed in the houses, as the birds tend to huddle together underneath and near the units, particularly during extremely cold weather.
  - Since no fans are used, the units' effectiveness continues even during power outages.
  - Forced air units vary in size from about 120,000 Btu to over 500,000 Btu.
  - These convection units rely on the fans within the force-air design units to circulate the heated air within the poultry house.
  - Like brooder heaters, all products of combustion are vented within the broiler house, so the heating efficiency of these gas-fired systems is usually assumed to be 100%.
  - Most broiler houses in the Ozark Highlands Plateau region are constructed with a minimum of 1,000,000 Btu total heating capacity; typically a farm's heating needs are met by a combination of brooders and forced-air heaters.
  - New requirements regarding heating systems (types of units, capacities, locations, etc.) are made by the region's integrators from time to time, requiring growers to update, modify, or enhance existing heating systems; for example, growers are increasingly required to have at least 20 brooders in that half of the production house used for half-house brooding.
  - An analysis of fuel consumption data recorded at the UA's Broiler Energy Research Facility (BERF) over a 16-flock period indicates that approximately 85% of the heating energy consumed in a typical broiler house can be provided by a gas-fired system consuming 3.7 gallons per hour, or an energy input of 344,100 Btu/hour.
  - For a biomass-fired furnace with an overall system efficiency estimated at 65%, this would equate to a required energy capacity of about 530,000 Btu/hour.

- For a typical 4-house farm there are three basic furnace-to-house configurations:
  - One furnace for each house
  - One furnace serving two houses
  - One furnace serving all four houses – the unit could, in theory, be located near the center, but transfer of the thermal energy from the furnace to the two outer houses would be a logistical challenge; a more realistic option for this configuration is to locate the furnace and introduce the thermal energy near the ends of the four buildings.
  - The first configuration would be the easiest to design, fabricate, and operate; the third configuration would likely be the least expensive on a cost-per-house basis.
- Some of the basic design assumptions and calculations used in this report include:
  - Wood pellet fuel:
    - Total annual quantity required to achieve the targeted 85% propane displacement = 34 tons/year @ 8,000 Btu/pound and 10% moisture content.
    - Maximum fuel consumption @ 85% displacement = 60 pounds/hour.
    - Required storage capacity for maximum consumption for a 10-day period = 7.2 tons.
    - Total annual ash production = 0.3 tons per year (0.6 cubic yards/year)
  - Litter fuel:
    - Total annual quantity required to achieve the targeted 85% propane displacement = 66 tons/year @ 4,600 Btu/pound and 50% moisture content.
    - Maximum fuel consumption @ 85% displacement = 115 pounds/hour.
    - Required storage capacity for maximum consumption for a 10-day period = 13.8 tons.
    - Total annual ash production = 13.2 tons per year (24.5 cubic yards/year)
  - Sawdust fuel:
    - Total annual quantity required to achieve the targeted 85% propane displacement = 66 tons/year @ 4,600 Btu/pound and 25% moisture content.
    - Maximum fuel consumption @ 85% displacement = 115 pounds/hour.
    - Required storage capacity for maximum consumption for a 10-day period = 13.8 tons.
    - Total annual ash production = 3.5 tons per year (6.1 cubic yards/year)
- Anticipated fuel storage and handling:
  - Pellets: transported, stored, and conveyed using off-the-shelf grain-based equipment
  - Litter: stored in on-farm stacking sheds, handled with on-farm front-end loader
  - Sawdust: stored in a fuel bunker, handled with on-farm front-end loader

- Additional furnace design considerations and assumptions:
    - Each system would be installed outside of the broiler house and would use outside combustion air.
    - Each system would use an air-to-air heat exchanger.
    - Each system would focus, at least initially, on 100% thermal output (not electrical).
    - Each system would also, if possible, serve as a mortality incinerator.
    - The bioenergy systems would be installed only on farms as a supplemental furnace system to meet the poultry houses' "base load" thermal requirements (i.e., target displacement of 85% of historical propane/ natural gas consumption); existing gas systems would continue to be used for peaking purposes (i.e., the remaining 15%).
    - The bioenergy systems would be installed on farms that have electric generators that would be able to run the furnace systems in the event of disruption of grid service.
    - The bioenergy systems would be installed on farms that have front-end loaders that the would be available for transferring sawdust/litter from the storage bunkers or stacking sheds to the furnace fuel supply systems.
    - A litter-fired system would be installed on a farm that has a stacking shed.
    - The primary control input for the system would be an in-house thermostat set by the farm manager.
- A pellet-, sawdust-, or litter-fired furnace would have the following components/attributes:
    - Fuel intake (& drying)
    - Ignition (e.g., automatic use of auxiliary propane for start-up)
    - Primary / secondary combustion
    - Variable operating levels (high turn-down ratio, not on/off)
    - Air-to-air heat exchanger
    - Heated air output blower
    - Exhaust stack for products of combustion
    - Ash collection and removal
    - Controls and monitoring system (a desired option would be off-site and real-time monitoring of performance parameters by the equipment supplier)

- Heat delivery and distribution:
  - Use of a water- or steam-based system was ruled out due to high plugging potential of the heat exchanger components inside the houses (confirmed through previous experiences).
  - Use of outside ducts ruled out for logistical/cost reasons.
  - Use of rigid metal inside ducts ruled out for logistical/cost reasons.
  - Plastic jet tubes were used with both furnace systems at UA BERF; the units were low-cost and performed satisfactorily.
- Deployment considerations:
  - Regional coordination: Vendors should identify and target growers within specific areas of concentrated poultry production for product sales, regardless of integrator affiliation; aggregation and subsequent export of ash from litter-fired furnaces should also be coordinated on a regional basis.
  - Target customers: Growers with reasonable access to a source of pellets (for pellet-fired systems), growers with reasonable access to sawdust (for sawdust-fired systems), growers that are not actively using their litter for agronomic purposes (for litter-fired systems – particularly those located in watersheds from which surplus litter needs to be exported); growers seeking an alternative for mortality management (for either litter- or sawdust-fired systems); or growers with existing houses (i.e., retrofit systems, not new units).
  - Sales strategy options: Direct sales to growers, sales through local poultry equipment supply companies, and lease programs.
  - After-sales support considerations: product warranties; operational support; and product servicing.
  - Feedstocks supply risks…what assurances can be obtain re supply of feedstocks and how can the risks be addressed (e.g., through insurance)?
  - Industry coordination…with both growers and integrators located in the target market.

- Economic analyses:
  - Annual revenues / economic benefits (A) = the value of the displaced propane; for litter-fired systems, revenues may also be realized from sale of the ash co-product.
  - Annual operating costs (O) = cost of the biomass fuel + transportation of the fuel to the furnace + system maintenance expenses + other (e.g., insurance).
  - Capital costs (C) = fuel storage & handling + furnace + hot air distribution component + ash storage
  - Overall feasibility = NPV (A) – NPV (B) – (C); if the result is positive then the investment appears attractive; if the result is negative, then the investment appears not. A summary of the economic analyses set forth in section 3.5 shows:

	wood pellets	broiler litter	low-grade sawdust
NPV of estimated benefits / revenues (Table 4)	$22,368	$24,152	$22,202
NPV of estimated annual expenses (Table 5)	($30,307)	($8,416)	($10,612)
NPV of estimated benefits less expenses	($7,939)	$15,735	$11,590
total estimated capital cost (Table 6)	($12,500)	($17,000)	($14,800)
summary net benefit (deficit)	($20,439)	($1,265)	($3,210)
result	not feasible under current conditions / assumptions	not feasible under current conditions / assumptions	not feasible under current conditions / assumptions

  - Capital costs (C) = fuel storage & handling + furnace + hot air distribution component + ash storage
  - However, numerous sensitivity/break-even analyses shown in section 3.5.6 indicate that the systems could be economically feasible at certain propane prices (and assuming the various assumptions noted in sections 3.5.1 and 3.5.6 are correct), such as:
  - Pellet-fired: at $1.38/gal-propane @ 85% displacement level & $250/house subsidy
  - Litter-fired: at $0.74/gal-propane @ 85% displacement level & $250/house subsidy
  - Pellet-fired: at $0.80/gal-propane @ 85% displacement level & $250/house subsidy

4.2. Conclusions

Farm-scale, biomass-fired furnace systems could, at least in theory, have both economic and environmental benefits for broiler producers. The large number of broiler houses in the U.S. represents a large potential market for a manufacturer of such systems. To be commercially successful, farm-scale biomass-fired energy systems must satisfy three criteria: 1) technically viable; 2) economically feasible; and 3) must be user-friendly (i.e., must be designed so that the level of effort and expertise required for operation is acceptable to the target customers).

An on-farm bioenergy system using litter feedstocks would be particularly attractive to the increasing number of farmers located in sensitive watersheds where there are increasing concerns associated with traditional land application of litter (and increasing interest in surplus litter management alternatives). Such a system could help growers utilize surplus litter while displacing increasingly expensive natural gas or propane. However, poultry litter is unique among biomass feedstocks and has numerous attributes that make it difficult to use and problematic as a fuel for combustion or gasification systems.

To date, no farm-scale biomass-fired systems have been designed that meet all (if any) of the three essential commercialization criteria. The design challenges have been particularly great for systems trying to use litter as fuel. Nonetheless, several equipment manufacturers and/or entrepreneurs are currently pursuing development of such systems for heating poultry houses, given the potential benefits of the systems…and the potential attractiveness of the furnace market.

Each of the three generations of furnaces developed and tested under this project using unprocessed biomass fuel incorporated significant technical improvements relative to the preceding generations. However, even the third-generation unit (Woody2) continued to experience substantial technical problems, and was unable to achieve satisfactory levels of operation with either of the primary target feedstocks (low-grade sawdust or broiler litter).

The prototype pellet-fired furnace system developed and tested under this project clearly demonstrated the many benefits of a system using pelletized biomass compared to unprocessed material. Key benefits include greatly reduced logistical challenges regarding fuel storage and handling, improved combustion performance, and enhanced ability to automate the entire system. These benefits apply to both pelletized litter and pelletized sawdust.

However, the costs associated with the pelletizing process—including transport of the raw material from the source to the pelletizing facility, then to the consumer (i.e., the broiler farm)—are very high and, under current conditions, appear to be prohibitive. New pelletizing or densification technologies are needed that:

a) Can utilize feedstocks with higher moisture content (e.g., up to, say, 30%), which would reduce (or even eliminate) drying requirements prior to the densification process;

b) Entail lower pressures and therefore less abrasion and longer service life for the pelletizer dies; and/or

c) Are mobile, so the system can be transported to the material, rather than transporting the material to the system as is currently the case.

Development of such improvements in pelletization (densification) technologies would also have enormous benefits for almost all bioenergy efforts worldwide. Support of such development seems to be an appropriate function for the U.S. Department of Energy (perhaps in concert with the U.S. Department of Agriculture through the joint agency Biomass Research and Development initiative; refer to www.bioproducts-bioenergy.gov).

About the Author

Jim Wimberly is President of the Foundation for Organic Resources Management (FORM), a nonprofit [501(c)(3)] organization established in 1997 that promotes environmentally and economically sound management of biodegradable, organic resources. Mr. Wimberly is a specialist in conservation and natural resources management, renewable energy, water quality, and program development; he works with both public and private sectors to develop and deploy effective strategies for resource management, deployment of appropriate technologies, and rural economic development, and has experience and expertise in technical, policy, and management arenas. As President of FORM he is responsible for program conceptualization and development, fundraising, project implementation (including administration of federal- and state-funded grants and cooperative agreements), and management and administration of the nonprofit organization (including human and financial resources and field offices).

Prior to joining FORM, Mr. Wimberly was Director of the Biomass Utilization Program at Winrock International, a nonprofit agricultural and resource management organization, where he managed Winrock's organics management and sustainable forestry programs and participated in organizational development activities, positions that entailed fundraising, program development, and project management. Prior to that position, Mr. Wimberly helped establish and served as Deputy Director of Winrock's international renewable energy program. Prior to that position, Mr. Wimberly served as Winrock's Contracts Officer, responsible for preparation of cost proposals, budget development/management, and administration of all prime and sub agreements for Winrock's program activities worldwide. Prior to his eleven years at Winrock, he worked with several other organizations and companies in international agricultural/rural development in the Pacific, Asia, Middle East, Africa, and Central America. Mr. Wimberly has a Masters Degree in Agricultural Engineering and a Masters Degree in Engineering & Business Administration.

Key Qualifications

Mr. Wimberly has more than 27 years' experience as a program/project manager and technical advisor in international agricultural development and natural resources management. He has worked in the United States and in more than 20 developing countries worldwide. Mr. Wimberly has both technical and business training and a wide range of professional experiences—from program development and economic/financial analyses to technical assessments, operations management, policy development, and project administration. Areas of expertise include:

- Program development: problem identification project conceptualization & design; grant writing and fundraising; and organization of human, institutional and financial resources for problem solving
- Project management and administration
- Economic and financial analyses
- Renewable energy, with emphasis in biomass energy systems & technologies
- Conservation and resource management, with emphasis on biological systems and water resources
- Facilitation, convening, stakeholder coordination, and consensus building
- Organizational development, including formation, start-up, & operations

Appendix 1: Additional Photos of the Pyro System at UA

Figure A.1.1: View of furnace and poultry house from the Southwest
Note the hot air duct from the rear of the furnace into the broiler house.

Figure A.1.2: View of furnace and poultry house from the Southeast
Note the hopper bottom pellet fuel storage bin (a conventional "off-the-shelf" bin locally available from poultry supply companies). The signage on the side of the bin explained the project objectives, activities, and participants.

Figure A.1.3: The furnace system

Note: The shed was required for prototype development and operations (including covering of the weigh bin system); it was anticipated that the commercial furnace units would not require a shed (the tube auger from the storage bin to the furnace would be weather-tight).

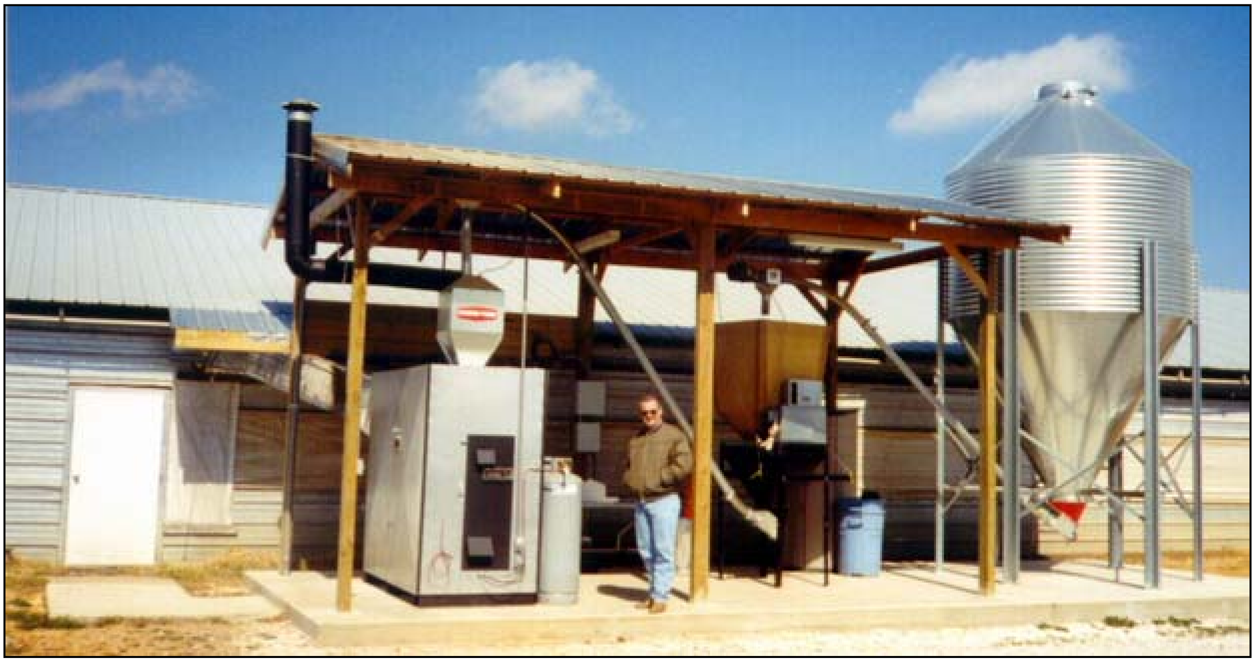
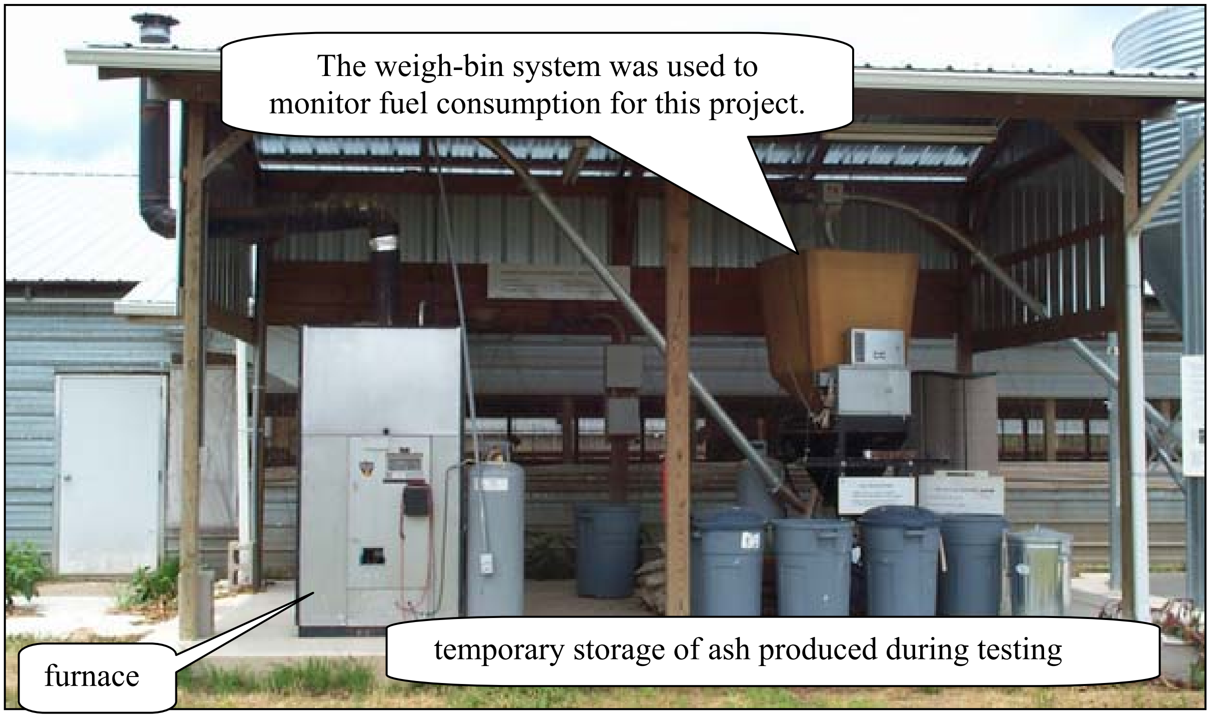


Figure A.1.4: Close-up of the furnace system

Note: The weigh-bin system would not be required for commercial installations.



Appendix 2: Additional Photos of the Dobson System at UA ("Chick")

Figure A.2.1: View of the system from the southwest

Note the modified feed wagon tested as a fuel supply device for sawdust and poultry litter. The system worked well, except for plugging of the outflow screw auger and the transfer auger (use of drag-chain or belt conveyors are recommended for future such installations). The fuel bunker is located on the other side of the feed wagon.

Figure A.2.2: Fuel bunker

Note: The bunker was constructed on a concrete slab with treated wood sidewalls. Tarps were used to shed rainwater (desired for sawdust and essential for litter).

Figure A.2.3: The furnace and the furnace shed

It was envisioned that the commercial unit would be weather-resistant and not require a shed. Note the 6-inch screw auger used to transfer fuel from the feed wagon to the furnace.

Figure A.2.4: The furnace inside the furnace shed

Figure A.2.5: Ceramic grate section

Figure A.2.6: Close-up of ceramic grate section

Figure A.2.7: System control and monitoring systems

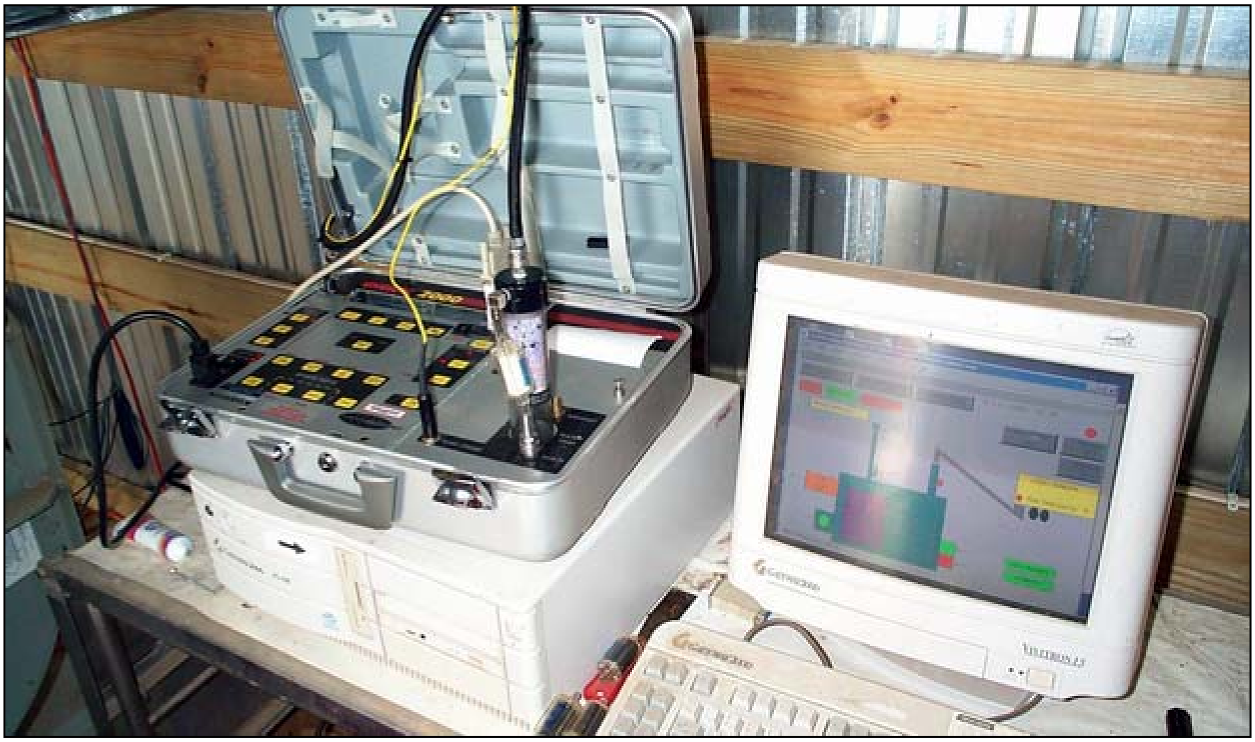


Figure A.2.8: UA project participants
From left to right: Richard Royal – furnace system operator; Tom Tabler – UA Broiler Energy Research Facility Manager; Tom Costello – UA Professor (Biological & Agricultural Engineering); Jim Wimberly – Foundation for Organic Resources Management

Appendix 3: Additional Photos of EP/WM's Woody1 system

Figure A.3.1: 3-Dimensional Rendering of the fuel supply and furnace system

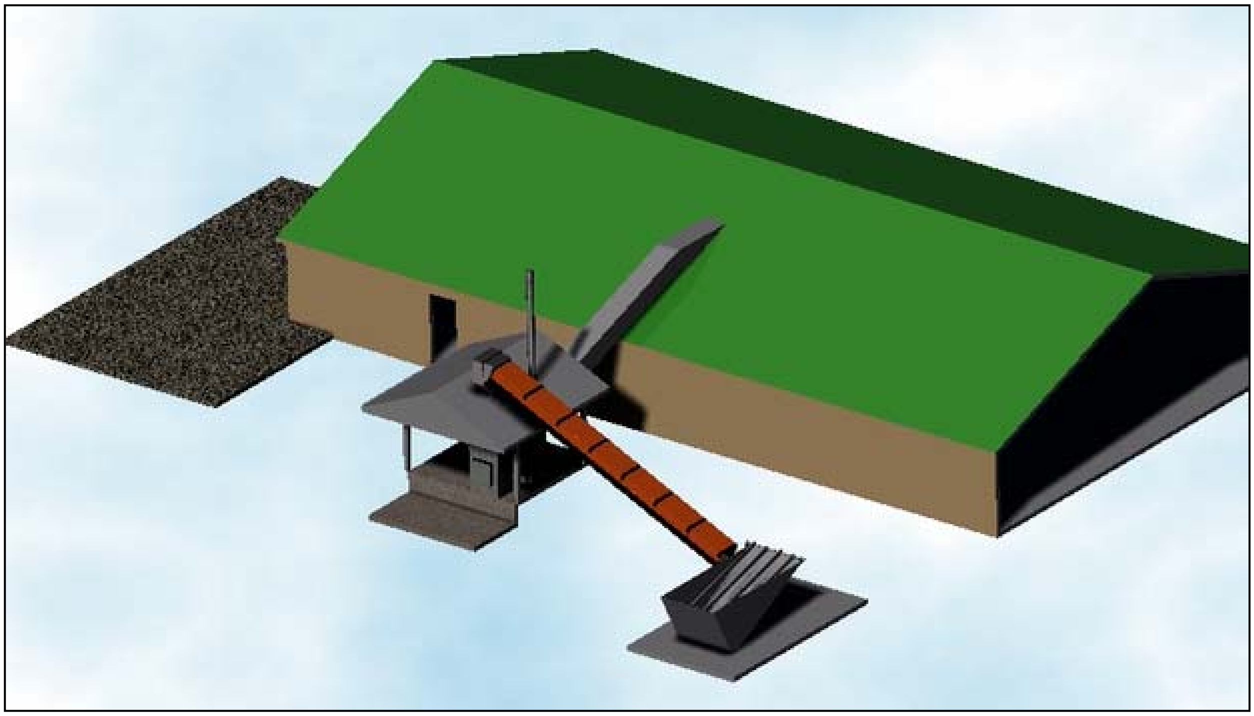


Figure A.3.2: Schematic of Woody1

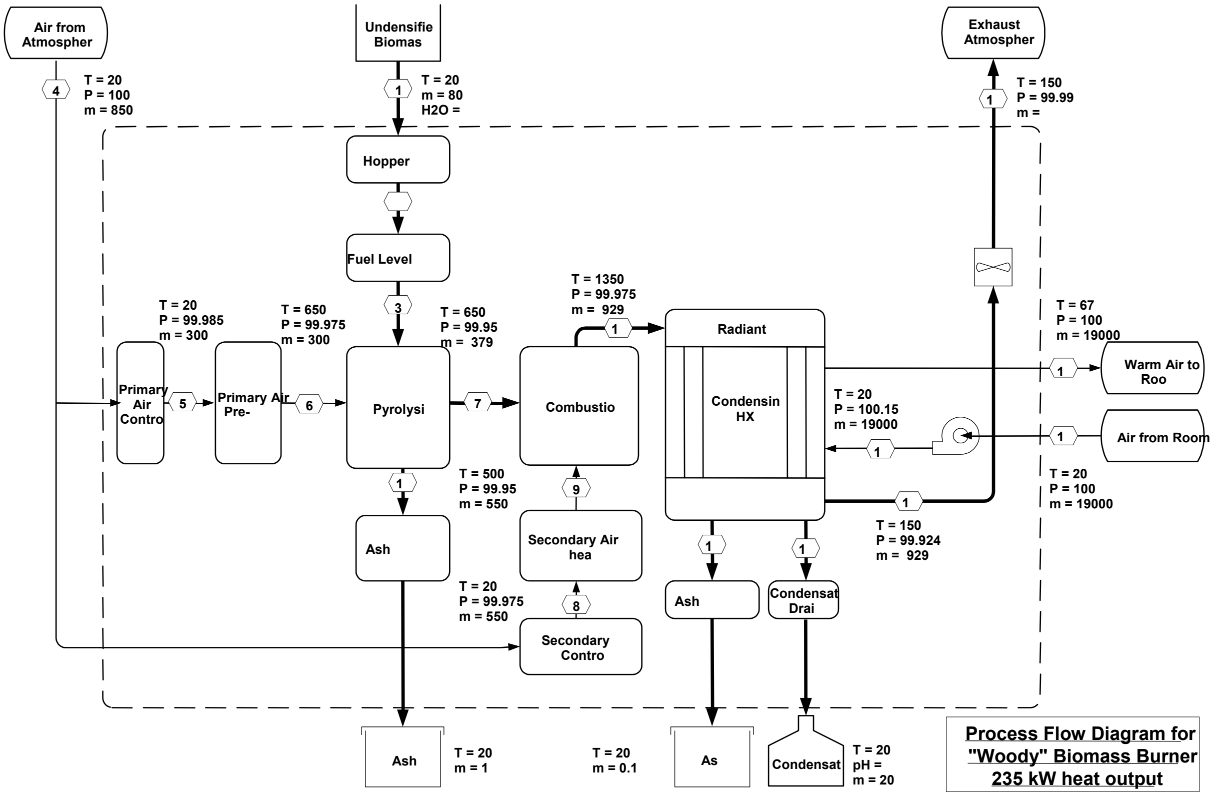


Figure A.3.3: Ceramic components during fabrication

Figure A.3.4: Initial performance trials

Figure A.3.5: Woody1 installation in Madisonville, KY

Figure A.3.6: Demonstration of Woody1 to regional poultry growers and others in Madisonville, KY (November 2001)

Figure A.3.7: Cracks in ceramic components

Figure A.3.8: Cracks in ceramic components

Considerable efforts were invested in system design and fabrication to minimize cracks in the ceramic components (which were caused by thermal stresses and reduced operating efficiencies).

Figure A.3.9: Slagging from litter testing

Figure A.3.10: Slagging from litter testing

The severe slagging that occurred during the litter testing was aggravated by use of rice hull-based litter; it is likely that less slagging would occur with use of wood shavings-based litter. Nonetheless, it was concluded that an alternate design of this furnace system was needed for use with litter fuels, given the physical and chemical nature of the material vis-à-vis the internal design of the furnace, regardless of whether the litter was hull- or shavings-based (or mixed).

Figure A.3.11: Screen shot of the improved controls & monitoring system

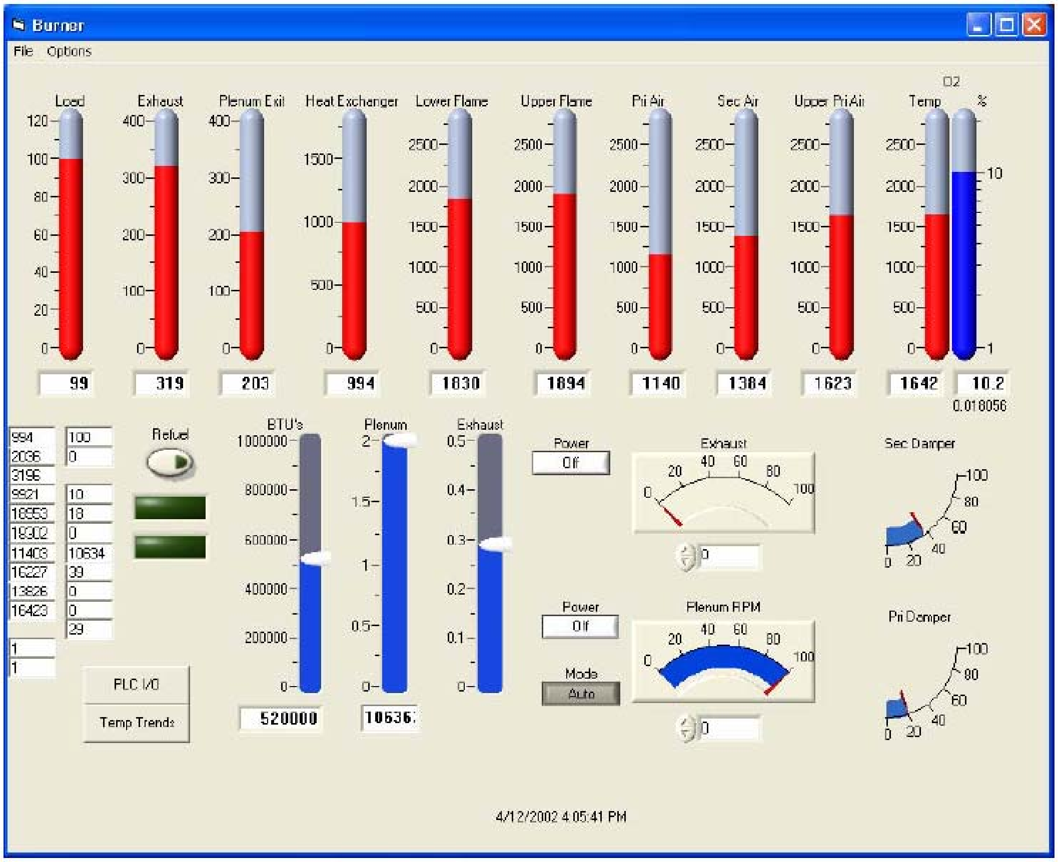
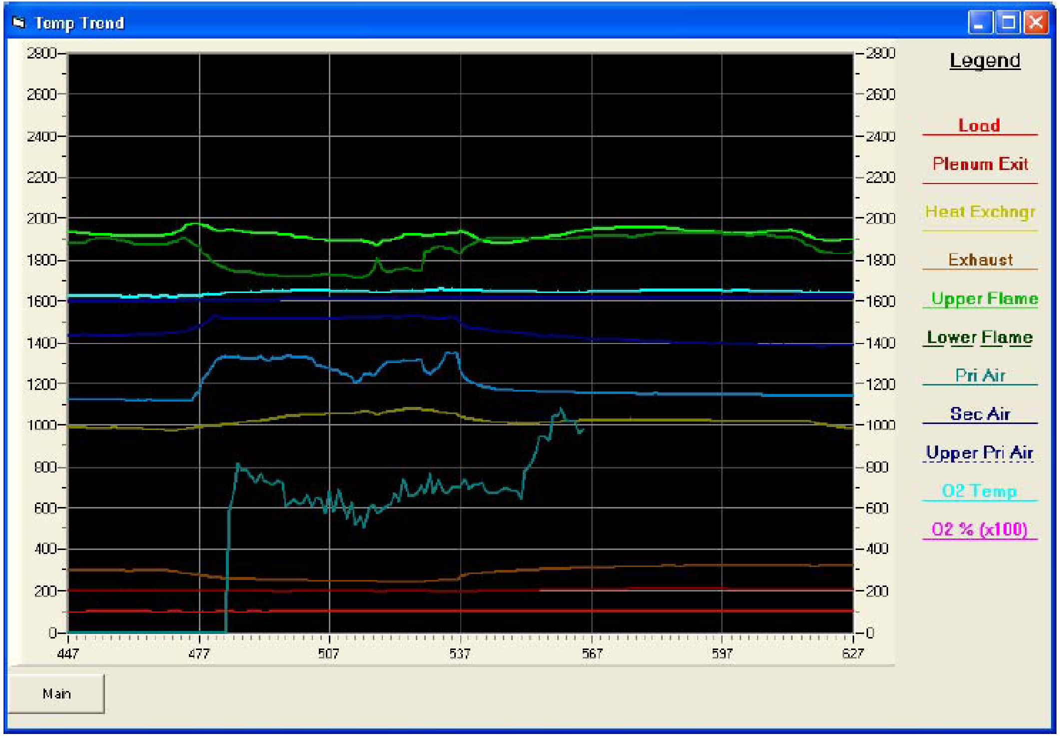


Figure A.3.12: Screen shot of the improved controls & monitoring system



Appendix 4: Additional photos of EP/WM's Woody2 system

Figure A.4.1: Improved design of casted ceramic components

Figure A.4.2: Completed fabrication of ceramic components

Figure A.4.3: Inside view of air-to-air heat exchanger (foreground) and heat deflector shield (background)

Figure A.4.4: Rear view of completed prototype showing commercial-design controls system on left side of unit

Figure A.4.5: Front view of completed prototype with metal skin installed and exhaust stack on right side of unit

Figure A.4.6: Complete system with feed bin, belt conveyor, and furnace system (inside shed)

Figure A.4.7: Shredded woody residue (from a RotoChopper) used by EP/WM for testing purposes

Figure A.4.8: White oak chips used by EP/WM for testing purposes

Figure A.4.9: Mortality going up the belt conveyor to the fuel intake chute during mortality incineration test

Appendix 5: Description and Analysis of Typical Broiler Litter

Broiler litter is a combination of bedding material and manure. Bedding materials used in Northwest Arkansas generally consist of pine shavings, rice hulls, or both. The type of bedding material used affects the physical characteristics of the resulting litter. The chemical characteristics of broiler litter vary according to the diet of the birds, the length of the grow-out cycle, methods of litter handling and storage, on-site management, and other factors. The following table provides the mean concentration of broiler litter constituents on a dry weight and an as-is basis from an analysis of 64 samples in Arkansas[1].

Variable	Units	Dry Weight Basis	As-Is Basis
Water Content	g/g	0.46	0.26
PH		7.88	---
E.C.	uS/cm	6783	---
Alkalinity	Mg CaCO3/kg	21160	14317
Total Elemental Analysis			
TKN	mg/kg	45,399	31,257
K	mg/kg	33,118	22,749
Na	mg/kg	8,401	5,807
S	mg/kg	7,682	5,270
Total P	mg/kg	22,121	15,201
Ca	mg/kg	34,309	23,508
Mg	mg/kg	6,995	4,796
Fe	mg/kg	942	651
B	mg/kg	55.6	38.4
Cu	mg/kg	526	365
Al	mg/kg	706	489
Mn	mg/kg	653	453
As	mg/kg	44.8	30.9
Se	mg/kg	16.2	11.1
Ni	mg/kg	16.5	11.3
Mo	mg/kg	5.71	3.94
Cr	mg/kg	8.28	5.71
Co	mg/kg	4.28	2.95
Water Soluble Components			
Soluble C	mg/kg	39,775	27,243
SOC	mg/kg	38,697	26,504
Sol. NH4-N	mg/kg	5,302	3,854
Exch. NH4-N	mg/kg	1,981	1,471
Sol. NO3-N	mg/kg	486	330
Zn	mg/kg	39.8	27.3
Pb	mg/kg	1.79	1.23
Cd	mg/kg	0.326	0.228

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[1] Moore, et.al. 1995. Final Report – Southeastern Poultry and Egg Association.

Appendix 6: Photos of low-grade sawdust supplies

Figure A.6.1: Medium-size sawdust pile in the Ozarks
Sawdust management consists of blowing and/or bulldozing the residue away from the production facilities, around the perimeter of the site.

Figure A.6.2: Small-size sawdust pile in the Ozarks
Sawdust management consists of blowing and/or bulldozing the residue away from the production facilities, around the perimeter of the site.

REPORT

TO

FOUNDATION FOR ORGANIC RESOURCES MANAGEMENT

ON

USE OF LIQUEFIED PETROLEUM GAS IN FOUR BROILER HOUSES FOR A THREE YEAR PERIOD
(1993~1996)

By

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June 30, 1999

USE OF LIQUEFIED PETROLEUM GAS IN FOUR BROILER HOUSES

INTRODUCTION

This describes the consumption of LPG (liquefied petroleum gas) during 16 broiler flocks grown over three years in four production-scale houses owned by the University of Arkansas. The primary purpose of the houses was to evaluate energy use in response to various structural and equipment features. The purpose of this report is to present the information on fuel consumption that may be useful for optimizing the capacity of solid-fuel furnaces for brooding broilers.

EQUIPMENT AND PROCEDURES

Broiler Houses. The four broiler houses were 40-ft by 400-ft in size, and were equipped with conventional feeding and watering equipment. The chickens were managed by procedures recommended by the integrator, Tyson Foods. A plastic-film partition in the center of the house length confined chickens to one-half of the house floor area for the first 10-14 days of brooding; thereafter, the chickens were allowed to occupy the entire house. House temperatures were regulated by heating at 85F for the first week, at 80F for the second week, at 75F for the third week, and at 70F for the fourth week. Thereafter, heating temperatures were set at 65-70F. As much as possible, the same thermal environments were maintained in all four houses, with the primary measurements being concerned with the energy required to maintain the desirable environments.

Houses #1 and #2 were constructed with steel frames and contained two inches of extruded polystyrene foam in the roofline, for a roof insulation value of R10. Houses #3 and #4 were constructed with wood posts and trusses, and contained about 5.5 inches of loose-fill of shredded cellulose between the lower chords of the trusses, for an insulation value of about R19. The sidewalls of all houses contained continuous 30-inch openings covered with a single layer of plastic film (curtains) during cold weather. Other wall areas were insulated with 1.5 inches of polystyrene foam, between the 1.5-inch lumber used for structural purposes.

Heating and Ventilating. Houses #1 and #3 were equipped with rather common heating and ventilating equipment for use during cold weather, and the overall system was designated as "conventional." Incoming ventilation air during cold weather was admitted through the south sidewall by lowering the curtains about ¾ inch. The brooding halves of the conventional houses were heated with 20 30,000-Btu/hr gas brooders (pilot ignition) and two 120,000-Btu/hr gas furnaces (unvented, with electric ignition). Ten of the same brooders were placed in the other half of these houses.

Houses #2 and #4 were equipped with unusual systems for broiler houses and were designated as "experimental." Incoming ventilation air was admitted through insulated, sliding doors, which were opened and closed by cable winches under the regulation of a static-pressure controller. These sliding doors were not distributed around the peripheral walls of the house, but were concentrated in a 60-foot wall section for the brooding end, and in two 100-foot sections for the entire house. This arrangement relied on a total of six ½-HP fans to ensure distribution of the incoming air, as well as heat from furnaces. The brooding halves of the experimental houses were heated with 12 30,000-Btu/hr gas brooders and three 170,000-Btu/hr gas furnaces.

For the first three flocks, the brooders were wired to come on first as temperature decreased, with the furnaces being ignited at a two-degree lower temperature. This arrangement was then reversed because the furnaces did not require manual lighting of the pilots for cool evenings. Short-term fuel measurements indicated that the pilots of the brooders consumed about 10% of the total brooder fuel, and provided unnecessary heating during many daytime hours. After the third flock, brooders were used for only the colder weather and as backup during power failures, because they were operable by 12-V battery power.

LPG Measurement. Temperature-compensated gas meters, equipped with senders, were placed on each house to measure LPG consumption. The gas from two 1000-gal tanks for each house was regulated to 10 lb/in^2, passed through the meters, and then was regulated to lower pressures for the brooders and furnaces. After correction for pressure and conversion to gallons, each meter pulse represented about 0.046 gallons of LPG. The meter pulses were counted by the electronic data collection systems on each house, and summed over 10-minute intervals. The gas meters were also read manually every day through brooding, and calibrated by comparing the meter readings with the deliveries of LPG through the three-year period.

The meter counts were converted to gallons as follows:

$$\text{LPG (gallons)} = (\text{count})(K)(1.648)/(36.4),$$

where 1.648 is the ratio of (10+atmospheric pressure)/(atmospheric pressure), 36.4 is the cubic feet of gas from one gallon LPG at STP, and K is the calibration coefficient determined from deliveries. The coefficients were 1.029, 1.072, 1.031, and 1.061 for houses #1, #2, #3, and #4, respectively.

Data Analyses. For simplicity, the first day of brooding for each flock was assumed to begin at noon on the day of delivery, even though actual placement might occur five hours before or after noon. In all cases, the houses were warmed to the desired brooding temperature before noon on the day of delivery. Preheating was assumed to include all LPG used before noon, and might include considerable use for one or two days before delivery, including fuel used for testing of equipment. Pulses from the gas meters were not usually counted during preheating, but the total fuel used for preheating was estimated from manual readings.

Occasional failures of the electronic recording system resulted in the loss of the 10-minute records, for as long as 19 days in one instance. Normally, the total amounts of LPG used over periods of one day or more could be estimated from the daily meter readings. In one case, the gas meter on house #2 was inadvertently bypassed for two weeks and the total LPG consumption was crudely estimated from readings of the LPG tank indicators. In another case, the electronic counter on house #4 failed through all early stages of brooding on flock 14, and this flock-house combinations was omitted from all following analyses involving time distributions of LPG consumption.

Initial data analysis consisted of totaling LPG consumption for the preheating and brooding periods of each flock-house combination. The average daily fuel consumption for each house-chicken age combination was then calculated and plotted. For these calculations, missing electronic counts were sometimes replaced by uniform distributions of the LPG estimated by other means.

All 10-minute measurements and one-hour sums were sorted into narrow classifications of fuel use in order to develop frequency distributions and to determine the relative importance of extreme rates of fuel consumption. For these calculations, missing data from electronic counters were not replaced by other estimates.

EXPERIMENTAL RESULTS

Flock-House Totals. LPG consumption for brooding and preheating for each flock-house combination is shown in Table 1. The average total fuel use for all houses through the three years was 37.7 gal LPG per 1000 birds. This is lower than a published regional average of about 50 gal/1000 birds from about 20 years earlier and probably reflects the impact of improved housing, even with improved bird performance.

The greatest fuel use in all houses was during flock 1. The coldest weather of the three-year period occurred at this time and coincided with the unfamiliarity of the flock manager with the new brooding systems. The major impact of seasonal variations in temperature on LPG use through the three-year period is clearly evident.

The LPG used for preheating was about 5.4% of the amount used for brooding. The fuel used for preheating included some experimentation for drying out the litter before chicken placement, so may be greater than used in commercial flocks.

The increased insulation in houses #3 and #4 decreased fuel use by 22% from the amounts used in houses #1 and #2. The ventilation and heating systems in houses #2 and #4 decreased fuel use by 25% below use in houses #1 and #3. Much of this decrease is credited to the use of the stirring fans for providing more uniform distributions of incoming ventilation air and heated air from the LPG furnaces.

LPG Use Versus Chicken Age. Figure 1 shows the rate of LPG use in gal/day versus chicken age for the four houses, averaged over 16 flocks. LPG use was always highest on the first day of brooding and steadily decreased until 10 days of age. The increases in LPG use after 10 days resulted from heating of the entire house after removal of the half-house partition. At this time, the previously unheated half of the building had to be warmed up, the building heat loss was doubled, and the smaller chicks didn’t provide enough body heat to fully compensate. During cold weather, the partitions were removed at 14 days. During warmer weather, the partitions were sometimes removed as early as 10 days to provide more feeder and watering space for the chickens, without significant increase in heating loads. Another peak in LPG use occurred on days 42 through 55; this is credited to some unusually cold weather during those days for flocks 1 and 6.

Table 1. Use of liquified petroleum gas (LPG) in four broiler houses over three years.

Flock and	Heating	Gallons of LPG per House by Flock				
Dates	Mode	House #1	House #2	House #3	House #4	Average
Flock 1: 19/Nov/90-	Preheat	313.0	110.8	64.2	226.0	178.5
13/Jan/91	Brooding	2,705.8	2,005.9	2,337.2	1,485.1	2,133.5
Flock 2: 1/Feb/91-	Preheat	68.3	4.5	32.4	35.8	35.2
27/Mar/91	Brooding	832.6	726.8	785.4	457.7	700.6
Flock 3: 5/Apr/91-	Preheat	40.9	31.8	8.3	27.7	27.2
9/Jun/91	Brooding	368.3	227.5	281.6	275.0	288.1
Flock 4: 20/Jun/91-	Preheat	13.3	14.8	24.4	8.9	15.3
18/Aug/91	Brooding	60.4	88.8	42.4	64.6	64.0
Flock 5: 29/Aug/91-	Preheat	18.4	11.4	11.4	0.0	10.3
23/Oct/91	Brooding	422.1	391.6	93.6	340.4	311.9
Flock 6: 12/Nov/91-	Preheat	126.7	140.0	100.2	99.4	116.6
7/Jan/92	Brooding	1,956.5	1,107.2	1,546.1	981.7	1,397.9
Flock 7: 23/Jan/92-	Preheat	0.7	68.4	49.3	0.0	29.6
16/Mar/92	Brooding	1,308.9	857.5	1,034.5	766.8	991.9
Flock 8: 2/Apr/92-	Preheat	97.5	54.6	59.7	46.7	64.6
21/May/92	Brooding	570.3	253.7	295.9	178.2	324.5
Flock 9: 8/Jun/92-	Preheat	0.1	0.0	0.2	0.0	0.1
10/Jul/92	Brooding	178.9	252.6	141.2	172.1	186.2
Flock 10: 7/Aug/92-	Preheat	0.8	8.6	0.0	0.0	2.4
1/Oct/92	Brooding	193.0	131.3	81.6	81.8	121.9
Flock 11: 15/Oct/92-	Preheat	8.6	39.1	3.7	17.4	17.2
10/Dec/92	Brooding	1,774.6	867.9	1,042.3	660.6	1,086.3
Flock 12: 21/Dec/92-	Preheat	0.9	0.0	1.3	0.0	0.5
14/Feb/93	Brooding	1,316.7	1,374.6	1,365.4	1,094.5	1,287.8
Flock 13: 2/Mar/93-	Preheat	44.0	190.5	48.1	0.0	70.7
29/Apr/93	Brooding	1,414.8	901.0	1,169.3	1,193.5	1,169.6
Flock 14: 11/May/93-	Preheat	6.2	0.6	6.8	0.0	3.4
6/Jul/93	Brooding	260.0	151.4	179.0	246.6	209.2
Flock 15: 9/Jul/93-	Preheat	0.0	0.0	0.0	0.0	0.0
2/Sep/93	Brooding	43.3	70.5	30.3	34.1	44.5
Flock 16: 17/Sep/93-	Preheat	8.4	9.2	0.0	11.5	7.3
12/Nov/93	Brooding	543.0	655.5	370.4	190.8	439.9
Average	Preheat	46.7	42.8	25.6	29.6	36.2
	Brooding	871.8	629.0	674.8	514.0	672.4
Preheat/brooding, %		5.36%	6.80%	3.80%	5.76%	5.38%
Flock Total		918.5	671.7	700.4	543.5	708.6
Per 1000 8-wk birds		48.86	35.73	37.26	28.91	37.69

Insulation Benefit, (H#1+H#2-H#3-H#4)/(H#1+H#2), %	21.78%
Ventilation Benefit, (H#1+H#3-H#2-H#4)/(H#1+H#3), %	24.93%

Frequency Analysis of LPG Use by 10-Minute Periods. Rates of LPG use during all 10-minute periods were sorted into bins (or ranges) according to magnitude, with incremental ranges per bin of 0.05 gal per 10-minutes. This yielded histograms and cumulative numbers of periods for each house, similar to the one shown for house #1 in Figure 1. Of about 126,700 (less missing data) 10-minute periods for all 16 flocks, about 80,000, or 63%, of the monitored periods were zero. Histograms for all four houses had similar proportions of the total time with little or no fuel use over the three years.

The minor peak in the histogram at the 0.675 gal per 10-minute rate in Figure 2 seems to be an artifact of the meter calibration and the choice of histogram ranges. With the meter calibration coefficient of 0.0466 gal/count in house #1, recorded counts of 14 and 15 were both included in the range of 0.65-0.70 gal per 10 minutes. In all lesser ranges, only one integer count was included in each range. The probable occurrence of similar artifacts in other 10-minute analyses lead to the use of hourly record for further analyses.

Ten-minute observations were considered important in the determining the maximum rates of LPG use. Table 2 gives maximum LPG rates for the higher house- flock combinations.

Table 2. Maximum LPG use during 10-minute periods.

House Number	Flock Number	Chicken Age	Time of Day	Amount of LPG, gal
#1	1	26	22:20	1.3516
	2	1	10:30, 10:50	1.3516(2)
	6	23	03:40	1.1651
	7	13	09:20	1.5380
	8	1	07:20	1.2117
	11	5	00:10	1.3050
	12	4	04:00	1.3516
	13	13, 14	several	1.6312(4)
#2	1	45	23:20	0.9711
	2	26	03:40, 04:20	1.0197(2)
	3	1	12:10	0.9711
	5	22	02:20-4:30	1.0439(3)
	6	31	16:10	0.9954
	7	2	22:40	0.9954
	13	13	09:30	1.5538
#3	1	9	20:40	1.0736
	2	1	02:00	1.0269
	7	18	03:10	1.1669
	13	14	22:00	1.4937
#4	1	54	19:00	1.0090
	2	1	09:00	1.1051
	3	1	12:30	1.0571
	5	22	03:50	1.1532
	13	13,14	10:10-10:40, 14:40	1.4414(4)

The maximum rate of LPG use of 1.6312 gal occurred during four 10-minute periods on days 13 and 14 of flock 13 in house #1. One of these occurred at 9:20 AM, on day 13, when the non-brooding end of the house was being preheated. The others were at 9:30 PM, 10:10 PM, and 11:30 PM that evening, probably before the chickens had fully migrated into that end of the house. The maximum rates for the other houses also occurred during flock 13, on days 13 or 14. The rate of 1.6312 gal/10-min represents a heating rate of about 910,000 Btu/hr, which is considerably less than the nominal manufacturers' rating of 1,380,000 Btu/hr for the equipment in both halves of the houses.

Several house-flock combinations had maximum fuel use rates on days 1-10 of brooding. The maximum rate observed in those periods was 1.3516 gal/10-min of LPG, which corresponds to a heating rate of about 754,200 Btu/hr. Houses #1 and #3 had rated heating capacities in the brooding halves of 840,000 Btu/hr and houses #2 and #4 had brooding capacities of 870,000 Btu/hr. Duty monitors were installed on the relays controlling the brooders and furnaces during the later flocks, and they indicated that both furnaces and brooders were both on continuously for nearly 10 minutes on all houses during day 13 of flock 13.

Total LPG Use Versus Rates of Use. The frequency of 10-minute periods at various fuel-use rates described fuel consumption, but did not provide all the information needed for conveniently optimizing the size of alternative heating systems. Therefore, the total amounts of fuel used in each of the 0.05 gal/10-min incremental rates were calculated. The result of these calculations applied to data from house #1 is shown in Figure 3. This analytical method had the advantage of ignoring zero values, because they did not contribute to total fuel use. The cumulative of the frequency (density) distribution provides a convenient method for estimating the cost of limiting the capacity of an alternative heating system. Unfortunately, the artifact noted in the frequency analysis was more strongly emphasized in this analysis, so subsequent analyses were performed with totals over one-hour periods.

Figure 4 shows LPG use in house #1in both density and cumulative functions versus the hourly rates of LPG use in gal/hour. The densities were calculated with increments of 0.2 gal/hour. Figures 5, 6, and 7 show the same relationships for houses #2, #3, and #4, respectively. Finally, Figure 8 gives the same relationships for pooled data from all four houses.

The charts provide a method for estimating how much heat demand, in LPG equivalents, would not be provided by a solid-fuel furnace of limited capacity. For instance, using Figure 8, with the pooled data, a furnace with a capacity equivalent to the energy provided by LPG at a rate of 4.0 gal/hour (or about 360,000 Btu/hr) could provide 88% of the total heating demand.

Prediction Equations for Modeling. The prediction curves in Figures 4- 8 are based on a two-parameter gamma distribution, with parameters alpha and beta estimated by the method of moments. Given alpha and beta, the distributions can be solved numerically using the EXCEL function GAMMADIST. The inverse of the cumulative distribution can be solved by GAMMAINV, which yields a value of x for a specified cumulative probability.

Table 3. Estimated parameters of the gamma distributions for houses #1-#4 and the pooled data.

Parameter	House #1	House #2	House #3	House #4	Pooled
Variance	1.9786	1.6531	1.5620	1.8013	1.7979
Mean	2.6095	2.1944	2.3432	2.2297	2.3770
Alpha	3.4415	2.9128	3.5151	2.7599	3.1425
Beta	0.7582	0.7533	0.6666	0.8079	0.7564

Table 3 gives the parameters for the gamma distributions, calculated from the experimental data. The parameters are related by the following equations:

$$\text{Mean} = \text{alpha} \times \text{beta}$$

$$\text{Variance} = \text{alpha} \times \text{beta}^2.$$

The equations show that beta increases both the mean and standard deviation linearly. A change in beta corresponds to changing the size of a broiler house without changing any other factors. For instance, if the size of a broiler house was increased by 50%, the total fuel use, beta, and the standard deviation (square root of variance) could all be expected to increase by 50%, with easy modification of the prediction equations.

Other changes in broiler houses, such as changed insulation levels, improved ventilation schemes, or transposition to another climate, would not be as easy to simulate. Further analyses of these data may provide some guidelines.

SUMMARY

Experimental data from three years of tests in four production-scale broiler houses were analyzed for the ultimate purpose of estimating the optimum size of solid-fuel furnaces for replacing all or part of the LPG or natural gas that is used for heating. The data analyses resulted in an equation for estimating the proportion of LPG that can be replaced by a solid-fuel furnace of given capacity.

Figure 1. Daily use of LPG for each house averaged over 16 flocks.

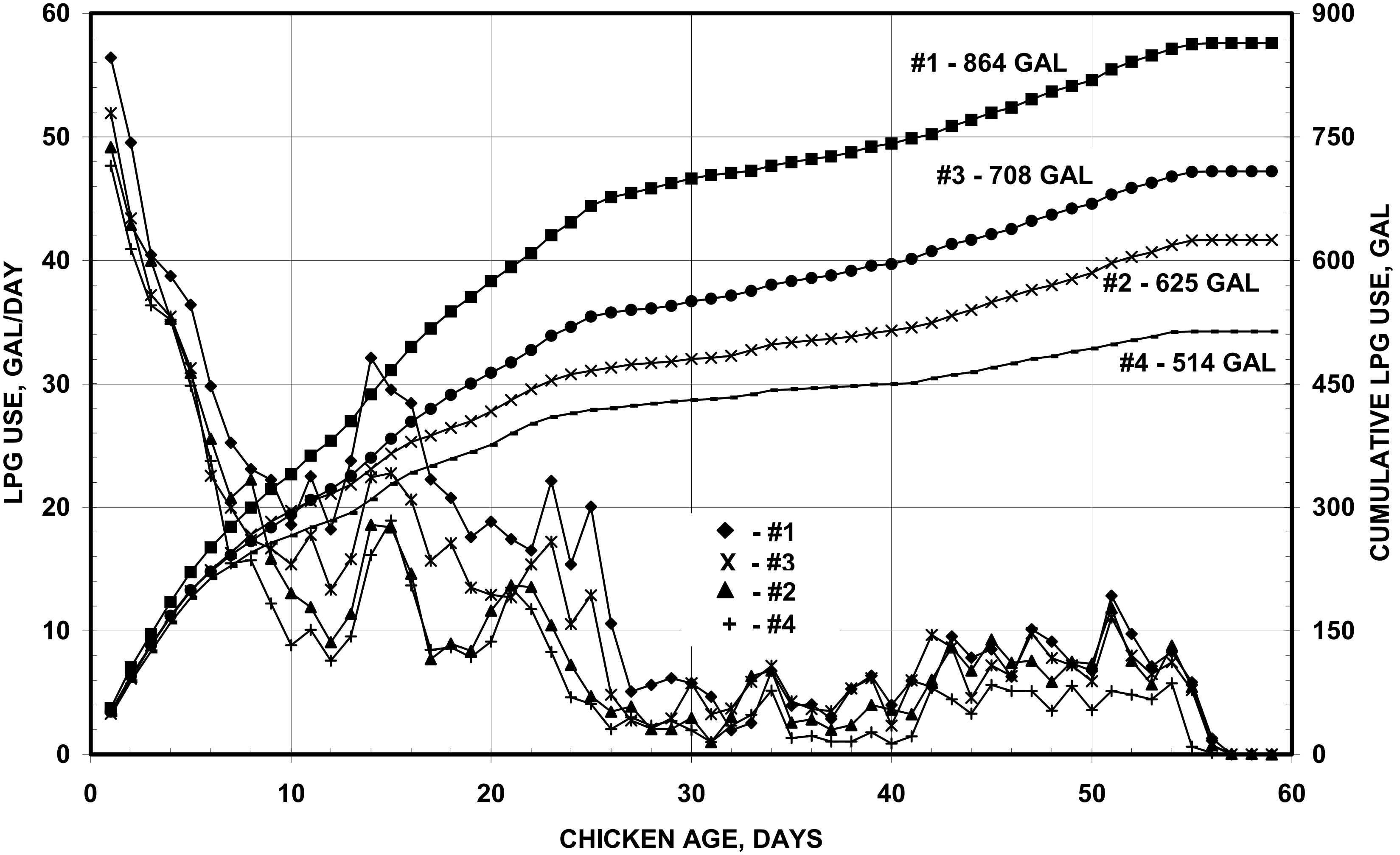


Figure 2. Density and cumulative numbers of 10-min periods for specified rates of LPG use in house #1.

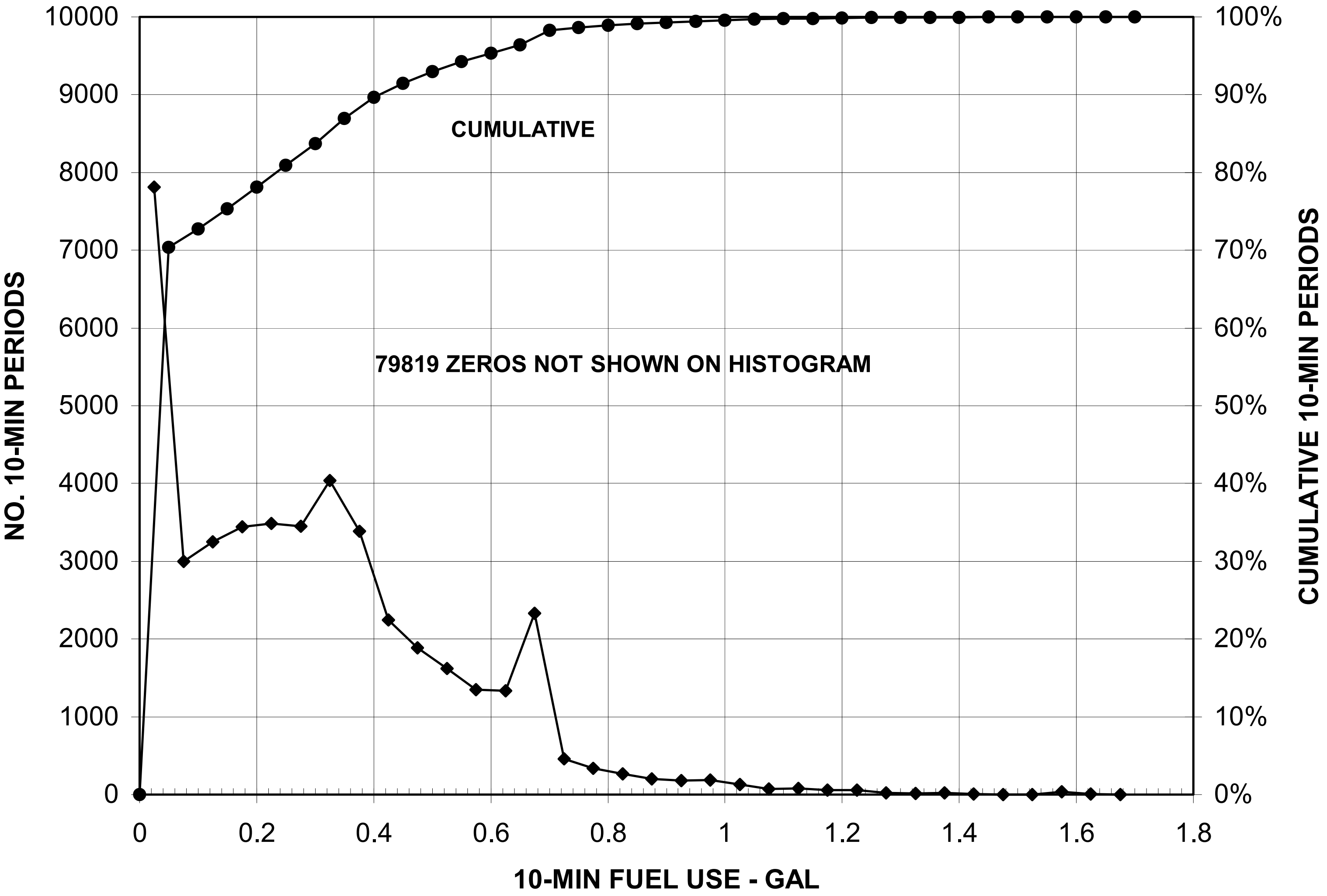


Figure 3. Density and cumulative amounts of LPG use for specified rates of use in house #1.

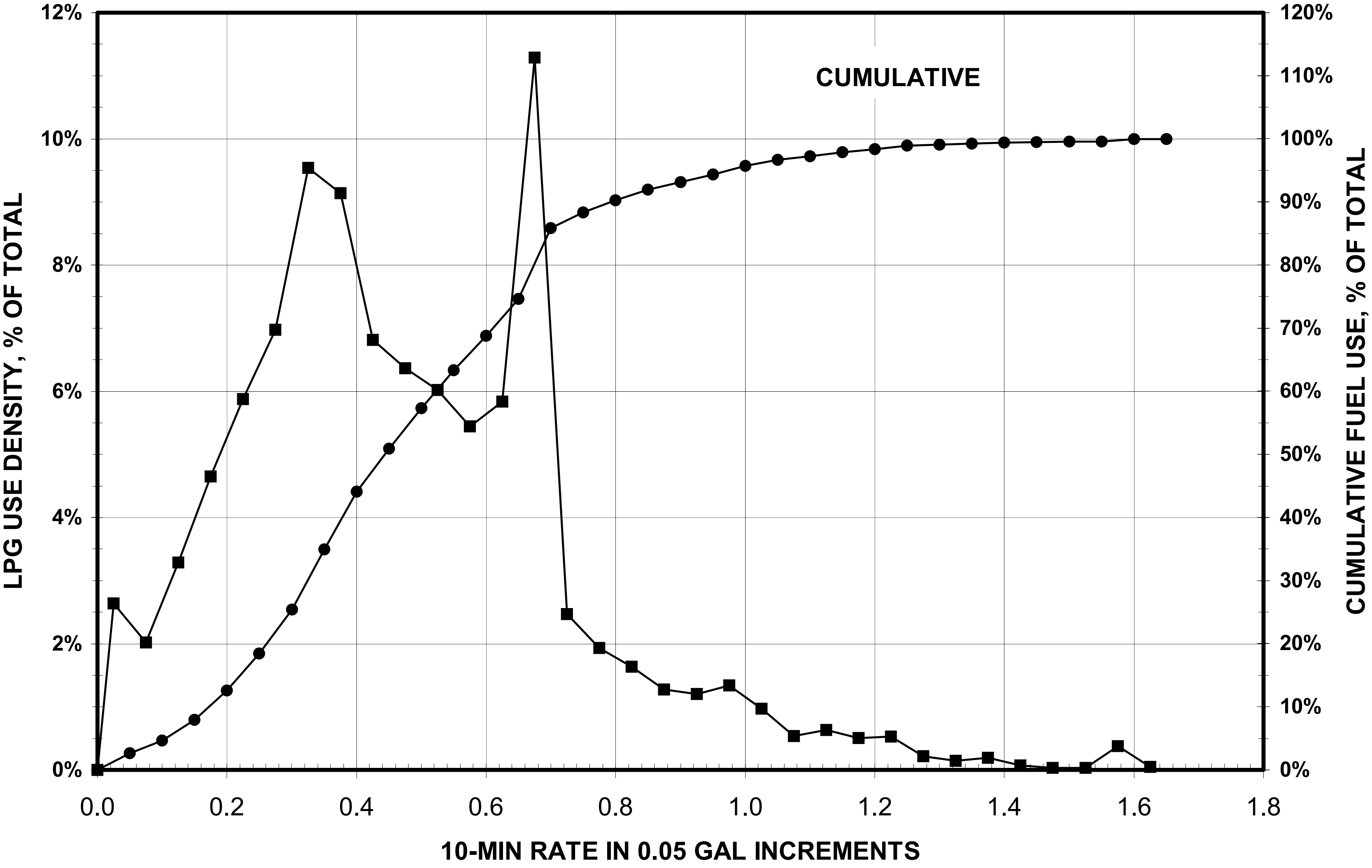


Figure 4. Percent of total LPG use versus 1-hr rate of use for house #1.

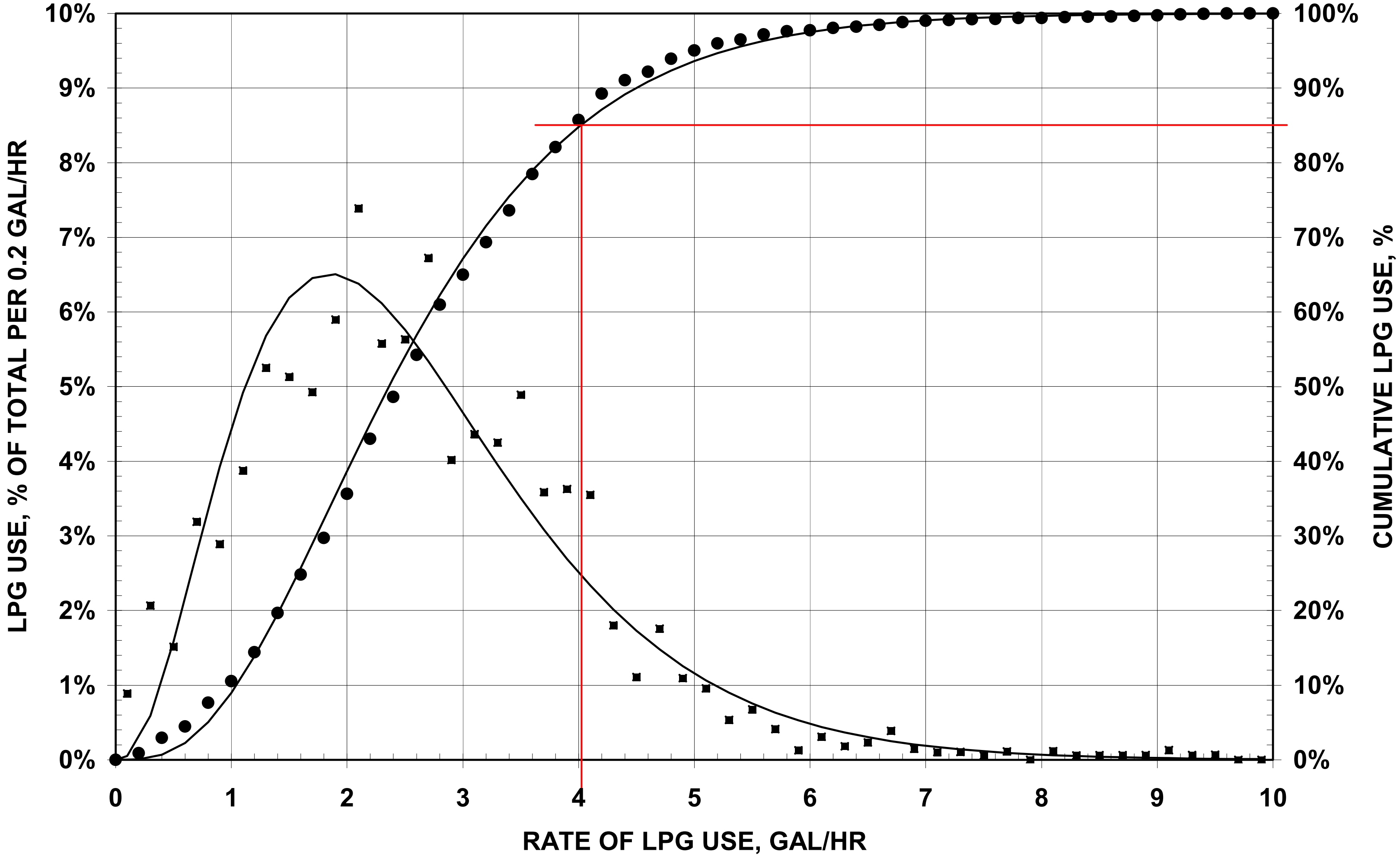


Figure 5. Percent of total LPG use versus 1-hr rate of use for house #2

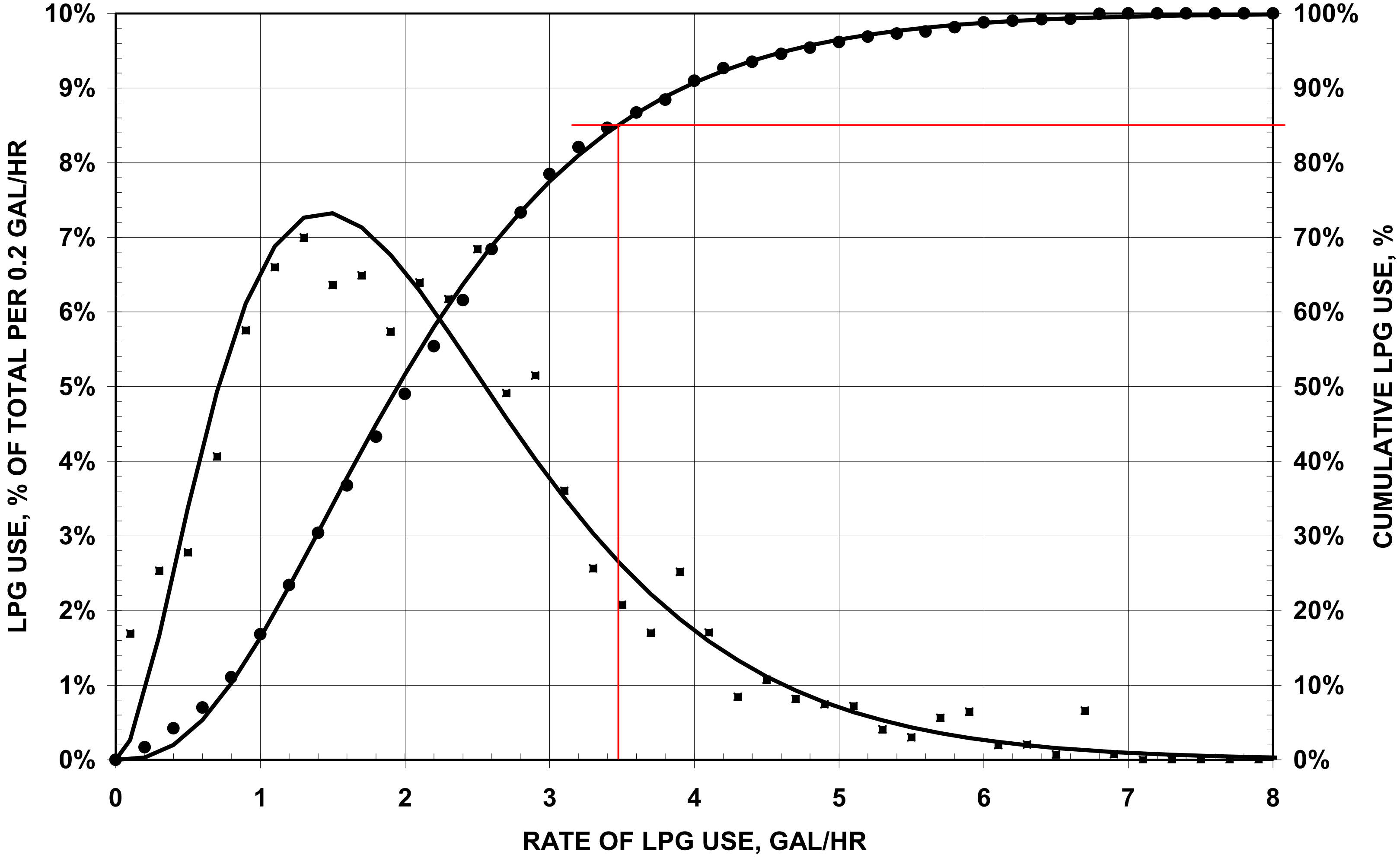


Figure 6. Percent of total LPG versus 1-hr rate of use for house #3.

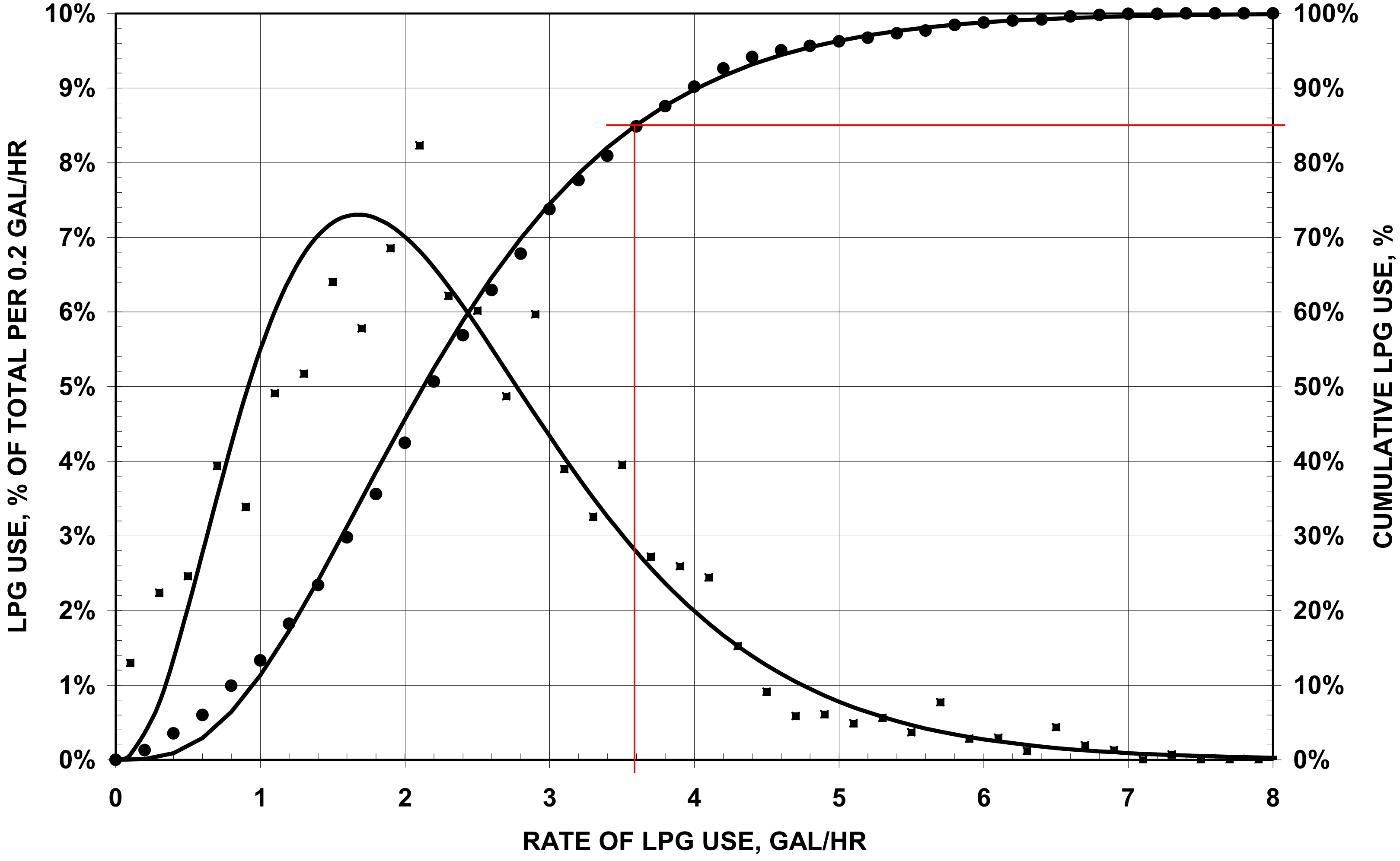


Figure 7. Percent of total LPG versus 1-hr rate of use for house #4.

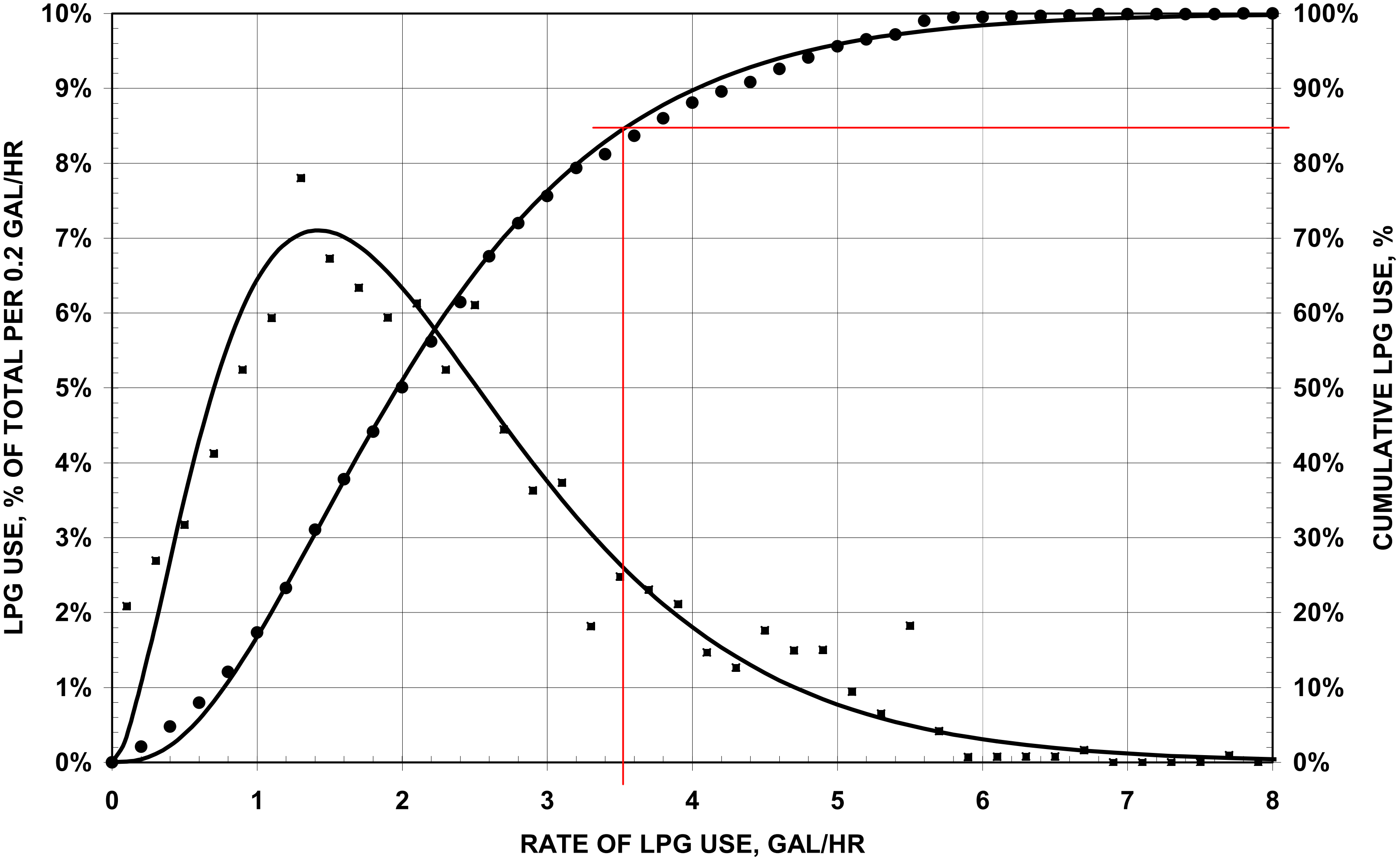
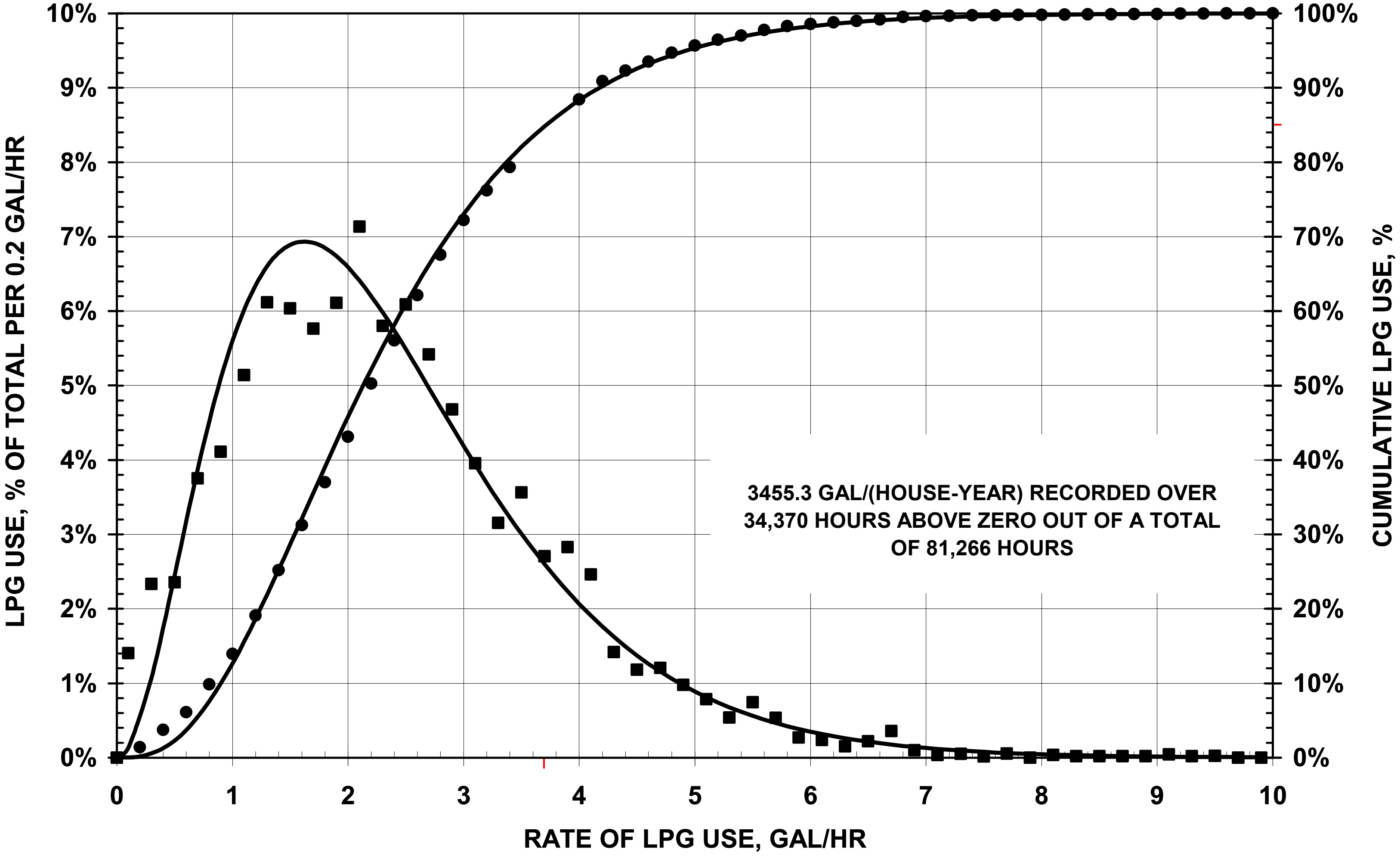


Figure 8. Percent of total LPG versus 1-hr rate of use for all houses.



Appendix 8: Flock Data (flocks # 35 ~ 72; 1996 ~ 2002)
University of Arkansas Broiler Research Energy Facility

Propane Use, gallons per flock

flock #:	35	36	37	38	39	40	41	42	43	44	45	46	*47	*48	49	50	*51	*52	53	54	55
house 1	1,343	1,320	811	381	134	343	1,308	1,381	595	81	52	819	1,440	955	280	264	1,119	1,867	1,290	218	197
house 2	1,793	1,761	865	543	195	308	815	1,041	498	41	68	625	1,100	580	172	168	620	1,553	856	208	149
house 3	1,133	1,169	686	441	153	322	1,014	1,373	1,027	76	47	412	264	467	153	99	271	519	756	151	181
house 4	2,165	2,041	1,018	762	331	591	1,702	2,060	903	167	163	1,168	1,638	838	448	209	834	2,365	1,323	344	257
averages	1,609	1,573	845	532	203	391	1,210	1,464	756	91	83	756	1,111	710	263	185	711	1,576	1,056	230	196

Electricity Use, kWh per flock

flock #:	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55
house 1	2,839	2,623	2,672	2,508	6,723	2,965	3,815	3,290	3,290	6,780	4,297	2,078	2,364	1,997	5,875	4,167	1,372	1,342	1,687	4,868	6,757
house 2	3,025	2,919	2,553	2,249	5,740	2,018	3,335	3,035	3,035	6,074	4,589	1,890	2,409	1,546	5,325	4,456	1,561	2,090	1,913	4,716	6,806
house 3	2,120	1,886	1,970	1,679	5,952	2,045	1,870	1,757	1,757	6,459	4,453	2,484	3,753	2,601	6,485	4,460	3,075	3,282	2,851	6,688	7,924
house 4	3,163	3,049	2,835	2,366	6,600	2,312	3,599	3,566	3,566	5,474	3,495	2,003	2,388	1,516	5,111	3,463	1,876	2,067	1,761	4,516	6,114
averages	2,787	2,619	2,508	2,201	6,254	2,335	3,155	2,912	2,912	6,197	4,209	2,114	2,729	1,915	5,699	4,137	1,971	2,195	2,053	5,197	6,900

Feed Conversion (pounds of feed per pound of bird)

flock #:	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55
house 1	1.78	1.75	1.87	1.94	2.08	2.07	2.07	2.07	2.09	2.20	1.91	1.77	2.06	1.94	2.26	2.08	2.03	2.08	2.16	2.16	1.91
house 2	1.81	1.81	1.74	1.87	2.05	2.01	2.02	2.03	2.03	2.08	2.06	1.79	2.17	2.08	2.22	2.13	2.11	1.94	2.12	2.08	2.07
house 3	1.84	1.68	1.85	1.86	2.04	2.03	2.07	2.07	2.10	2.17	2.06	1.78	2.11	2.02	2.28	2.16	2.13	1.98	2.18	2.16	2.00
house 4	1.80	1.75	1.84	1.91	2.06	2.02	2.05	2.01	2.09	2.02	2.08	1.75	2.12	2.12	2.32	2.11	2.13	2.08	2.24	2.18	2.04
averages	1.81	1.75	1.83	1.90	2.06	2.03	2.05	2.05	2.08	2.12	2.03	1.77	2.12	2.04	2.27	2.12	2.10	2.02	2.18	2.15	2.01

Propane Use, gallons per flock

flock #:	56	57	58	59	60	61	62	63	**64	65	66	67	**68	69	70	71	72	averages	minimum	maximum
house 1	744	2,906	1,680	723	531	150	365	911	2,152	1,931	948	178	184	1,280	2,040	1,220	425	910	52	2,906
house 2	747	2,780	1,245	625	367	154	231	724	2,640	2,418	521	312	81	1,313	2,042	1,041	344	830	41	2,780
house 3	556	2,694	1,363	984	478	145	342	1,321	2,521	2,255	788	261	88	1,258	2,246	1,219	490	782	47	2,694
house 4	791	3,121	2,420	1,351	749	380	295	1,094	2,372	2,583	928	627	147	1,036	2,082	1,188	641	1,135	147	3,121
averages	710	2,875	1,677	921	531	207	308	1,013	2,421	2,297	796	345	125	1,222	2,103	1,167	475	914	83	2,875

Electricity Use, kWh per flock

flock #:	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	averages	minimum	maximum
house 1	1,270	1,627	3,946	1,941	4,180	5,701	1,016	1,948	2,754	2,579	2,444	4,736	4,162	2,817	2,938	2,757	3,356	3,276	1,016	6,780
house 2	1,657	3,146	1,995	1,541	3,589	5,824	820	1,847	2,622	2,703	2,832	5,846	4,766	2,137	1,905	1,600	1,976	3,108	820	6,806
house 3	1,999	2,402	2,430	1,754	4,071	5,925	754	1,122	1,732	1,739	1,646	4,492	4,385	1,811	1,824	1,627	2,256	3,093	754	7,924
house 4	2,142	2,214	2,549	2,022	3,501	6,356	1,736	1,823	2,649	2,402	2,913	5,635	4,779	1,868	2,005	1,586	2,312	3,140	1,516	6,600
averages	1,767	2,347	2,730	1,815	3,835	5,952	1,082	1,685	2,439	2,356	2,459	5,177	4,523	2,158	2,168	1,893	2,475	3,154	1,082	6,900

Feed Conversion (pounds of feed per pound of bird)

flock #:	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	averages	minimum	maximum
house 1	1.92	1.96	2.20	1.87	1.95	1.96	1.74	1.88	2.10	2.01	2.05	2.03	1.85	1.88	1.89	2.03	1.52	1.98	1.52	2.26
house 2	1.94	2.07	2.07	1.87	1.80	1.86	1.74	1.88	2.21	2.00	2.01	1.93	2.09	1.99	1.97	1.85	1.84	1.98	1.74	2.22
house 3	1.94	1.94	2.08	1.98	1.81	1.88	1.74	1.78	2.66	1.98	2.04	2.02	1.92	1.83	1.89	1.78	2.05	2.00	1.68	2.66
house 4	2.02	2.07	2.05	1.98	1.92	1.86	1.74	1.87	1.99	2.09	2.05	2.04	4.37	1.87	1.87	1.87	2.01	2.06	1.74	4.37
averages	1.96	2.01	2.10	1.93	1.87	1.89	1.74	1.85	2.24	2.02	2.04	2.01	2.56	1.89	1.91	1.88	1.86	2.00	1.74	2.56