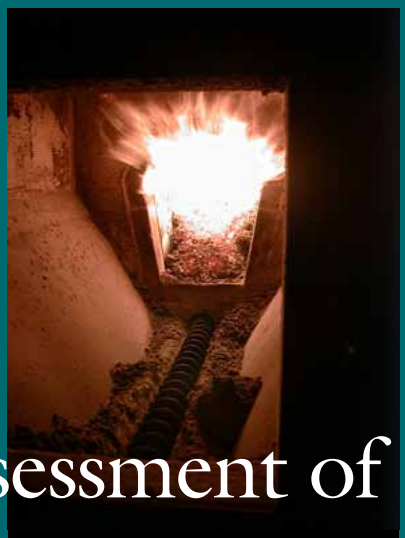
FINAL REPORT • JANUARY 2011



Technical Assessment of Grass Pellets as Boiler Fuel in Vermont

A Report by the Vermont Grass Energy Partnership

Acknowledgments

The Vermont Grass Energy Partnership is a collaboration among the Vermont Sustainable Jobs Fund, University of Vermont Extension Service, and the Biomass Energy Resource Center. While these partners have made this initiative possible and are responsible for this report, we would like to express our appreciation to several key players.

Our thanks go to:

- Chris Davis of the Meach Cove Trust, without whose efforts and countless hours during the combustion trials this study would not have been possible.
- Averill Cook and Charlie Agnew of Biomass Commodities Corporation.
- John Gammie of Gammie Air Test Monitoring LLC.
- Kevin Anderson of Twin Ports Testing, Inc..
- Chris Brooks and Matt McKinstry of Vermont Wood Pellet Company.
- Roger Rainville of Borderview Farm.

Project Partners

Each of the three partners has a vested interest in grass energy in Vermont and different and complementary areas of expertise. The University of Vermont's Extension Service has vast experience in the agronomic end of the equation. The Biomass Energy Resource Center holds the pelletization and fuel combustion experience and expertise. Vermont Sustainable Jobs Fund is expert in both liquid bio-fuels and developing new models that help green businesses succeed.

The following provides further information about the three partner organizations.

Vermont Sustainable Jobs Fund (VSJF)

VSJF, a not-for-profit organization located in Montpelier, was created by the Legislature in 1995 to accelerate the development of Vermont's green economy. VSJF uses early-stage grant funding and technical assistance to catalyze and accelerate the development of markets for sustainably produced goods and services. Its current focus is on the intersection between sustainable agriculture, sustainable forest products, and renewable energy in the form of bio-fuels.

University of Vermont and UVM Extension Service

As Vermont's land-grant college, the University of Vermont has a mission to serve the citizens of Vermont by conducting timely and applied research as well provide outreach education through its UVM Extension programs. UVM Extension offers a vast array of outreach programs for farms, communities, and businesses. Within its agricultural outreach programs, it has recently and is currently focusing on renewable energy, particularly the sustainable production and utilization of oilseed crops for on-farm biodiesel production and perennial grass crops for biomass energy.

Biomass Energy Resource Center (BERC)

BERC is a national nonprofit based in Montpelier, Vermont, whose mission is to achieve a healthier environment, strengthen local economies, and increase energy security across the United States through the development of sustainable biomass energy systems at the community scale. BERC is an independent and impartial organization that conducts fair and objective studies, maintaining complete neutrality while conducting routine due diligence on biomass resource supply for projects and government agencies. In addition to its work on wood fuels, technologies, and applications, BERC is working to expand the use of agricultural biomass as a viable fuel for community energy projects.

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Technical Assessment of Grass Pellets as Boiler Fuel in Vermont

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The Vermont Grass Energy Partnership and this report were funded through the generous support of US Senator Patrick Leahy through a grant from the US Department of Energy.

EXECUTIVE SUMMARY

The Vermont Grass Energy Partnership explored the potential for grass energy in Vermont, identified challenges in the supply chain (from field to end energy use), and developed possible solutions to those challenges.

BACKGROUND

Vermont has been a national leader in biomass energy for several decades. There is a well-established energy marketplace for using wood to produce heat and electricity to meet our energy needs with local, renewable resources.

Although Vermont has abundant forestland and wood resources, it also has roughly 84,000 acres of idle cropland[1] and an indeterminate but significant amount of marginal farmland that could also be suitable for perennial grass cultivation. With fewer working farms, more landowners are brush hogging hay crops rather than harvesting them. At the same time, energy costs continue to rise, and events such as the recent coal mine explosions and the Gulf of Mexico oil disaster are reminders of the need to utilize renewable energy sources and reduce the use of fossil fuels.

Today in Vermont, there are farmers interested in growing energy crops. There are homeowners interested in heating with grass in their pellet heating systems. There are pellet heating appliance vendors claiming their device can "burn anything." In short, there is a need for credible information to answer the questions about whether grass energy has real potential and, if so, how it should be implemented.

VERMONT GRASS ENERGY PARTNERSHIP

The University of Vermont's Extension Service (UVM Extension), the Vermont Sustainable Jobs Fund (VSJF), and the Biomass Energy Resource Center (BERC) have teamed up to form the Vermont Grass Energy Partnership (VGEP) in an effort to explore the potential for grass energy in Vermont, identify challenges in the supply chain (from field to end energy use), and develop possible solutions to those challenges.

GRASS PELLET STUDY

This study was conducted in order to learn more about the:

- growing and harvesting of various perennial grasses.
- preprocessing of and pelletizing the grasses.
- performance and viability of these grasses as a heating fuel used both alone and when blended with wood.
- resulting air emissions.

Three diverse grass hay types, all perennial grasses, were selected for the study:

- **Switchgrass (*Panicum virgatum*) hay.** Switchgrass is not commonly found in Vermont but has been shown in other parts of the United States to be a promising biomass crop.
- **Reed Canarygrass (*Phalaris arundinacea*) hay.** Reed canarygrass is a commonly found, productive grass in Vermont and is well adapted to a wide range of conditions, particularly wet, marginal soils.
- **Mulch Hay.** Mulch hay represents hay that is not well suited for livestock due to poor quality and is often sold in the "mulch" market for conservation purposes.

Although the study covered a very broad area from growing grass to burning it, it did not include any economic or market analyses to determine the feasibility of the business of making and selling grass pellets. Additional studies are in process addressing those aspects.

The switchgrass and reed canarygrass used in this research were obtained from test sites overseen by Dr. Sid Bosworth, UVM Extension agronomist, during the 2009 growing season.

The mulch hay was supplied by Meach Cove Trust of Shelburne, Vermont. VSJF, BERC, and UVM staff mechanically chopped the 40-pound grass bales and the chopped grass was reground, blended, dried, and pelletized by the Vermont Wood Pellet Company (VWP) in North Clarendon, Vermont in early January 2010. Finished pellet fuel samples were taken by VWP staff and chemical analysis and mineral composition of the 13 different pellet types were performed by Twin Ports Testing, Inc. in February 2010.

TEST BURNS

The test burns were conducted by Meach Cove Trust staff in a 500,000 Btu/hour Solagen (pellet) combustion unit located at the All Souls Interfaith Gathering in Shelburne, Vermont and overseen by BERC and Biomass Commodities Corporation (BCC) personnel. The combustion trials for the stack emissions testing were conducted in March 2010 by Gammie Air Test Monitoring LLC for the 100% grass samples and wood control. Further combustion trials were conducted in April 2010 with the assistance of BCC to assess the grass pellet fuel blends under normal "real world" combustion conditions.

GRASS BLENDS

The three grass types (switchgrass, reed canarygrass, and mulch hay) were tested both "as is" (100% grass) and at three proportional levels (25%, 12%, and 6%) blended with wood. A sample of 100% wood pellet fuel was used as a control against which the grasses could be compared. During pelletization, the 100% grass blends encountered some logistical problems. Grass fiber alone does not flow very well and tends to bridge and ball up very easily. The pellets formed with 100% grass tended not to be as well formed as the wood/grass-blend pellets. This can be attributed to the low levels of lignin in the material as well as the higher moisture content of the grass fibers.

ASH CONTENT

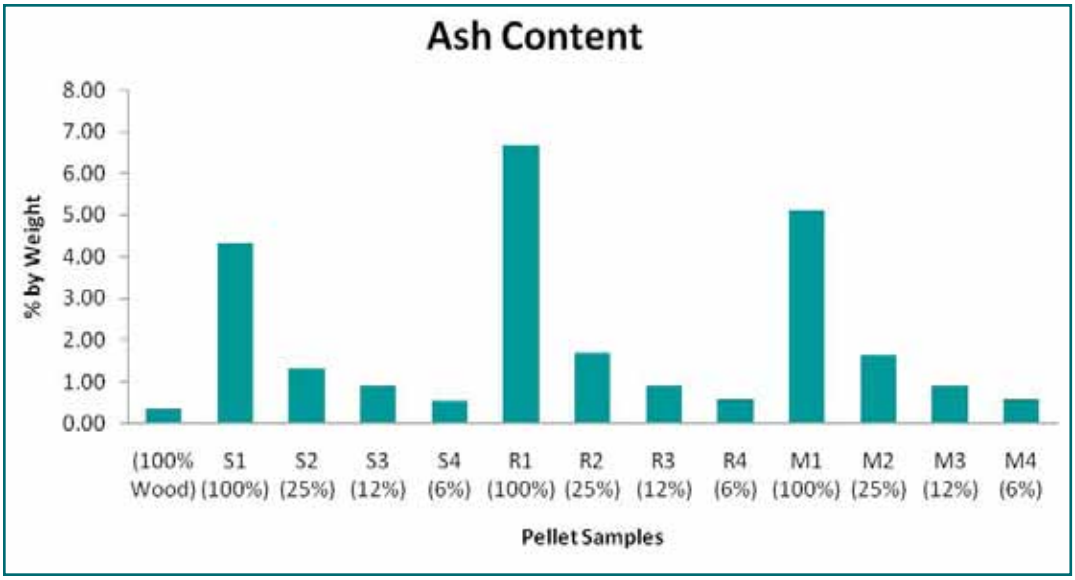
As expected, the ash contents of 100% grass blends were high (4.3-6.7%), dramatically higher than a premium-grade wood pellet (<0.5%). The 100% switchgrass and mulch hay pellets would receive the "utility-" or "industrial-" grade for fuel quality as defined by the Pellet Fuels Institute (PFI)—100% reed canary grass pellets contained ash content too high for PFI categories for pellet quality. The 25%, 12%, and 6% blends obviously had lower ash contents than the 100% grass blends. Of the three grasses, 100% switchgrass had the lowest ash content at 4.3%.

Three diverse grass hay types, all perennial grasses, were selected for the study:

- **Switchgrass**
- **Reed canarygrass**
- **Mulch hay**

EXECUTIVE SUMMARY *(cont'd)*

Of the three grass varieties, switchgrass had the lowest emissions for both particulates and NO_x.



The energy value of the grasses was good and switchgrass even had a slightly higher (2%) energy value than the wood control. Reed canarygrass had 10% lower energy content than wood and mulch hay was only 8% lower. Ash fusion temperatures for the minerals contained in the grasses were determined and the results indicated temperatures hotter than typical combustion temperatures would be needed for comprehensive fusion of ash minerals.

Despite this laboratory result, fused minerals or "clinkers" were formed during operational combustion trials. All three grass types contained significantly higher concentrations of nitrogen, sulfur, and chlorine than the wood. Higher concentrations of nitrogen and sulfur can result in increased emissions of oxides of nitrogen (NO_X) and oxides of sulfur (SO_X) when combusted. Additionally, higher-chlorine concentrations in the fuel can release corrosive gases when burned that can deteriorate the inside of boilers and exhaust ducts and stacks.

STACK EMISSIONS

Stack emissions testing focusing on particulate matter and NO_X were conducted for the 100% wood, 100% switchgrass, 100% reed canarygrass, and 100% mulch hay pellet fuels on the 500,000 Btu/hour Solagen boiler at All Souls Interfaith Gathering.[2] Other than good system controls and a skilled system operator, no further emission control devices exist at the test site. The current regulatory air emission limits in Vermont apply only to larger systems—greater than 3 MMBtu/hour capacity.

The results of these emissions tests were as expected—grasses containing higher concentrations of ash and nitrogen than typical wood fiber emitted more particulates (both coarse and fine) and more NO_X. Of the three grass varieties, switchgrass had the lowest emissions for both particulates and NO_X.

While NO_X emissions are important, Vermont has not set limits for boilers. Only extremely large boilers (250 MMBtu/hour and larger) trigger federal emissions limits for NO_X.

At this time, the US Environmental Protection Agency (EPA) has proposed new stringent rules dramatically lowering the allowable limits for particulate matter. These rules are yet to be finalized, but will likely require more sophisticated and costly emissions control technologies to be used on any new system boilers (wood pellet or grass pellet-fueled), even on smaller-sized boilers.

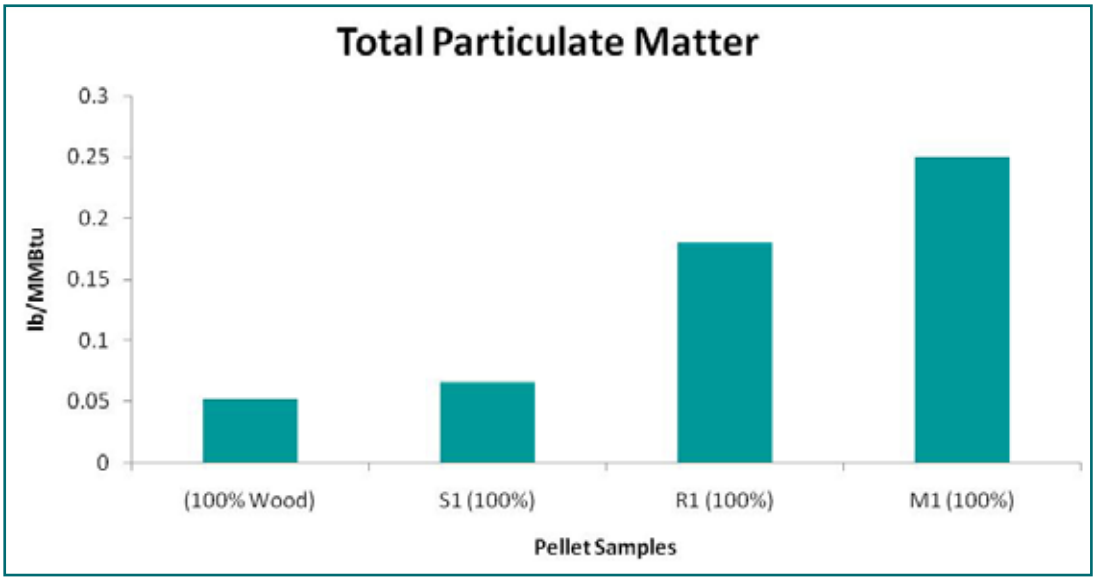
"REAL WORLD" COMBUSTION TESTS

Further combustion tests were performed for the 100%, 25%, and 12% blends. These combustion tests were designed and conducted to assess how the system would perform using these different pellet fuels and what problems the system would experience.

Each combustion test burn lasted approximately three hours and basic system performance was monitored (O_2, CO, CO_2, combustion chamber temperature, and stack gas temperature). In addition, anecdotal information, such as the amount and consistency of the ash, was observed.

Each grass pellet was successfully burned with varying degrees of supervision, adjustment, and maintenance. All three grass pellet types performed best with the greatest concentrations of wood in the fuel. Mulch hay pellets were extremely difficult to combust and much effort was made to adjust the system to be able to burn them. Even the switchgrass pellets produced a substantial amount of glassy clinkers that proved operationally challenging (hard to clean out, blocked new fuel in-feed, and blocked air flow in combustion chamber).

Each combustion test burn lasted approximately three hours and basic system performance was monitored (O_2, CO, CO_2, combustion-chamber temperature, and stack gas temperature).



EXECUTIVE SUMMARY *(cont'd)*

VGEP is continuing to examine new and existing heating appliances (furnaces and boilers) that claim the ability to reliably burn high-ash fuels such as grass pellets.

KEY LESSONS LEARNED

In Vermont, hay crops and dedicated energy grasses can be successfully grown and harvested using conventional methods and existing farm equipment. Hay and energy grass can be successfully pelletized into various densified fuel form factors (briquettes, large diameter "pucks" or tablets, and small-diameter pellets). These materials can be blended at varying concentrations with readily available wood fibers to increase overall pellet fuel quality.

Pure grass pellets should not be sold for use in residential pellet stove heating appliances designed to burn wood because of the high ash content of grass pellets and their corrosive flue gas. There is potential, however, for their use in larger boilers and heating systems that have been engineered to meet these challenges using adjustable feed rates, traveling grates to break up clinkers, appropriate air and emission controls, and corrosion resistant materials such as stainless steel. Other potential end uses would be in smaller appliances that have been specifically engineered to meet the challenge of high-ash grass pellet fuel.

Today, there are numerous companies that claim to have equipment able to "burn anything," but there are few which have demonstrated that their equipment will perform reliably using grass fuels. Therefore, VGEP is continuing to examine new and existing heating appliances (furnaces and boilers) that claim the ability to reliably burn high-ash fuels such as grass pellets. This research is needed to identify the most suitable heating appliances for this fuel.

GRASS ENERGY DEVELOPMENT STRATEGIES

VGEP has identified two principal strategies for expanding grass fiber use as a heating fuel in Vermont:

1. Blend grass with wood pellets to meet existing industry norms for fuel and appliances.
2. Build a new market for 100% grass fuel by identifying or developing the appliances capable of burning grass fuels. Additionally, minor adaptation of wood pellet manufacturing equipment and processes may be necessary to better suit the material-handling characteristics of grass fiber.

Vermont is experiencing slow and steady growth of pellet deliveries in bulk to smaller commercial and institutional heating customers. The first option could provide fuel to meet this growing demand by blending grass and wood fibers (i.e., 10-20% grass and 80-90% wood) to produce a PFI Standard grade fuel pellet for use in boilers in the 250,000-1.5MMBtu range. Heating systems of this size (and up) are typically slightly more tolerant as far as pellet fuel quality is concerned, opening the way to utilize grass- and wood-blended fuels.

To fully assess the potential of this market, further economic feasibility work should be conducted to determine the production costs of pellets made with grass and wood blends and to gauge the interest of the pellet-consuming market for this type of product.

The second strategy (developing a new market capable of burning 100% grass pellets) also warrants further examination. Despite the prevalence of wood pellet- and woodchip-fueled heating in Vermont, there may be a niche market opportunity for 100% grass fuels. For instance, replacing fossil fuels with grass pellets on Vermont farms is a logical opportunity as farms can produce and possibly utilize the grass fuel to replace their No. 2 oil and propane for heating buildings and greenhouses.

An economic assessment needs to be conducted to determine the production costs of farm-scale grass pelletization and the potential fuel savings of grass pellets over other heating fuels. Other market development scenarios using 100% grass pellets could emerge that will need further in-depth analysis as well.

As a result of this study and supporting research by others, VGEP maintains that it is in the interest of both the pellet fuel consumer and the pellet fuel manufacturing industry that customers know fully the quality and performance differences between grass and wood pellets. Grass pellet marketers must therefore communicate effectively as to the likely operational challenges of using grass fuels.

NEXT STEPS

The next steps in determining the feasibility of grass energy in Vermont should include a robust economic assessment of the costs of manufacturing grass pellets under different scenarios. For instance, what changes can be anticipated at a centralized (stationary) pellet mill compared to utilizing mobile equipment (at different scales) to process the grass "on location?" As part of this economic assessment, key variables such as the cost of energy (fuel, electricity, diesel, biodiesel, etc.), subsidies paid to farmers (e.g., USDA's Biomass Crop Assistance Program), and economies of scale in production costs must all be considered. Once the grass pellet production costs are fully understood, target wholesale and retail price points can be projected and compared against other heating fuels, including liquid fossil fuels and wood fuels.

As a result of this study and supporting research by others, it is in the interest of both the pellet fuel consumer and the pellet fuel manufacturing industry that customers know fully the quality and performance differences between grass and wood pellets.

INTRODUCTION

HISTORY OF THE VERMONT GRASS ENERGY PARTNERSHIP

Vermont has a long tradition of using biomass for energy. For thousands of years, humans have used wood as an energy source for cooking and heating. To this day, many Vermonters continue to use wood to heat their homes. In addition to residential heating, over the past few decades, woodchips also have been used as fuel for heating dozens of facilities and generating electricity at two power plants in Vermont.

Yet Vermonters continue to consider other options for sourcing energy and fuels locally, and grasses have become another popular consideration. Based on prior research, Vermont farmers, entrepreneurs, researchers, and renewable energy advocates see that there is an opportunity to source biomass fuels from Vermont's agricultural land through dedicated energy crops such as grasses, in addition to the wood fuel from our forests. While in other parts of the United States, especially in the Midwest, grasses are increasingly being used for fuel (e.g., co-firing at coal power plants), the use of grass as a source of energy is only in the research phase in the Northeast.

Vermont's agricultural lands provide opportunity to source biomass fuels through dedicated grass energy crops.

Over the past five years, the interest in using grasses for energy has been rising nationwide and in Vermont. Vermont has a significant number of under-utilized acres of farmland at risk of growing back to forest or being developed. There is a real desire to utilize this land area, provide farmers with new sources of income, and help meet energy needs with local renewable sources of energy. Meanwhile many biomass combustion system vendors make claims of "burning anything;" however, numerous systems that have experimented with grass fuels have reported significant issues with ash fusion and even corrosion of interior linings of heat exchangers and exhaust stacks.

While grass energy is very compelling in concept, there are numerous challenges that need further exploration. In an effort to identify these challenges and find solutions, the Vermont Grass Energy Partnership (VGEP) was formed between the University of Vermont's Agriculture Extension Service (UVM Extension), the Vermont Sustainable Jobs Fund (VSJF), and the Biomass Energy Resource Center (BERC).

In 2008, the three VGEP members began to explore the potential for perennial grasses grown in Vermont to meet a portion of the state's heating demand and reduce the consumption of non-renewable fossil fuels. Early-stage agronomic research from Cornell University, REAP Canada, and others encouraged the formation of VGEP. Together, the partnership worked to better understand the issues facing grass energy and identify possible strategies to advance the concept. It has been investigating agricultural best practices for high-biomass producing perennial grasses, pelletization of grass and grass/wood blends, and testing the performance and emissions of grass pellet fuels in high-efficiency biomass heating systems.

OBJECTIVES AND SCOPE OF WORK

The objective of the VGEP study is to perform a detailed evaluation of the chemical composition, combustion performance, and air emissions of the various pelletized grass feedstocks and to compare these results against woody biomass fuels as the established alternative to fossil fuels.

The following is an explanation of the work performed:

1. Harvesting perennial grass samples from UVM's test fields: switchgrass, reed canarygrass, and mulch hay.
2. Fabricating the biomass fuel hopper adapted for the specific boiler room at the All Souls Interfaith Gathering in Shelburne, Vermont.
3. Grinding, mixing, and pelletizing of the various feedstock mixtures performed at Vermont Wood Pellet Company in North Clarendon, Vermont.
4. Analyzing the chemical and mineral composition of the wood pellets (control fuel) and grass samples (test fuels) performed by Twin Ports Testing, Inc.
5. Testing for air emissions performed on the 500,000 Btu/hour Solagen boiler (designed and operated using wood pellets made from 100% wood fiber) at the All Souls Interfaith Gathering facility.
6. Testing efficiencies and ash sampling during combustion trials conducted by the Biomass Commodities Corporation at the All Souls Interfaith Gathering facility.
7. Analyzing and reporting on the gathered data.

The Vermont Grass Energy Partnership has been investigating:

- **agricultural best practices for high biomass producing perennial grasses,**
- **pelletization of grass and grass/wood blends, and**
- **testing the performance and emissions of grass pellet fuels in high-efficiency biomass heating systems.**

INTRODUCTION *(cont'd)*

Due to the abundant information indicating the troublesome high-ash content of the grasses tested, four blend concentrations with wood fiber were explored that would result in reducing ash content in the blended fuel pellet.

The work carried out by VGEP closely examined the technical feasibility of using grass as a feedstock for pellet making and its use as a heating fuel in boiler heating systems; specifically, examining the growth, harvesting, pelletization, and final combustion of grass fuel. This final report is a summary of the work and findings of VGEP. The results of this multi-phase analysis will eventually lead to recommended strategies on how best to cultivate and utilize grass energy in Vermont.

METHODOLOGY

Two-dozen 40-pound square bales for each of the three grass types being tested were sourced from select farms. Grass was pre-chopped, reground, blended with wood fiber, and pelletized to specification. (Further details on how these grasses were grown and pelletized are provided in the following sections of this report on grass types and sourcing and pelletization.)

Twelve blends of grass pellet were designed based on the three grass types being studied here: switchgrass ('S' series), reed canarygrass ('R' series), and typical mulch hay ('M' series). Due to the abundant information indicating the troublesome high-ash content of these grasses, four blend concentrations with wood fiber were explored that would result in reducing ash content in the blended fuel pellet (wood fuels have much lower ash content than grasses).

For each of the grass types, the following grass and grass/wood blends were produced: 100%, 25%, 12%, and 6% grass, based on weight. For this report, pellets containing 100% grass fiber were S1, R1, and M1; pellets containing 25% grass fiber were S2, R2, and M2; and pellets containing 12% grass fiber were labeled S3, R3, and M3. Pellets containing 6% grass content were S4, R4, and M4. The table on the next page illustrates these blends.

Test Blend	Grass Fiber Content	Wood Fiber Content
Control (100% Wood)	0%	100%
S1 (100% Switchgrass)	100%	0%
S2 (25% Switchgrass)	25%	75%
S3 (12% Switchgrass)	12%	88%
S4 (6% Switchgrass)	6%	94%
R1 (100% Reed Canarygrass)	100%	0%
R2 (25% Reed Canarygrass)	25%	75%
R3 (12% Reed Canarygrass)	12%	88%
R4 (6% Reed Canarygrass)	6%	94%
M1 (100% Mulch Hay)	100%	0%
M2 (25% Mulch Hay)	25%	75%
M3 (12% Mulch Hay)	12%	88%
M4 (6% Mulch Hay)	6%	94%

Twelve blends of grass pellets were designed for this study.

The resulting pellets were sampled and shipped to a laboratory for ultimate and proximate analysis as well as several other test parameters such as ash fusion temperature and chlorine content. A quarter ton of each test pellet blend was transported to the boiler room at the All Souls Interfaith Gathering facility. Here a new test fuel hopper was fabricated and the fuel feeding system was constructed to bypass the main pellet fuel storage and feeding line. Biomass Commodities Corporation personnel calibrated this new test fuel feed line to interface with the combustion control system. Combustion trials were conducted for stack emissions testing and "real world" combustion conditions.[3] Lastly, a 100% premium-grade wood pellet produced by Vermont Wood Pellet Company was used as a control and a point of comparison for the grass pellet blends.

The performance of the boiler (designed and operated using wood pellets) was compared for each of the blends of grass pellets in terms of ease of combustion and quality and quantity of ash. The various blends of grasses were tested to identify the optimum blend that would perform well and not require excessive system maintenance. All tests on the grass pellets were also conducted on the control wood pellet samples.

GRASS TYPES AND SOURCING

Left to right: switchgrass, reed canarygrass, and mulch hay.



GRASS TYPES

There are numerous grass species and varieties that could be explored as a dedicated energy crop. Some species are native to Vermont and others are not; some are well studied and others are better known in other parts of the country.

UVM has been actively examining grass species and varieties for decades to better understand which varieties and production practices are best for forage as a livestock feed in Vermont; however, there was very little work evaluating these same species when managed for biomass as an energy crop.

After the various pros and cons were weighed, two perennial energy grasses were selected for examination: switchgrass and reed canarygrass. In addition, a typical Vermont "mulch" hay made up of a mixture of commonly grown forage species was chosen to examine as a comparison.

Switchgrass is a native, perennial, warm-season grass that historically has not been grown in Vermont because it is does not have the quality potential for dairy and livestock that cool-season grasses have. Because of its seasonal growth pattern and lower ash content compared to other grasses, however, it has been shown to be a promising biomass crop in other parts of the United States.

Reed canarygrass is a commonly found, productive grass in Vermont and is adapted to a wide range of conditions, particularly wet, marginal soils.

Mulch hay represents hay that is not well suited for livestock due to poor quality and is often sold in the "mulch" market for conservation purposes.

GRASS SOURCING

Switchgrass hay was harvested in November 2009 from a three-year-old quarter-acre stand of 'Cave In Rock' switchgrass located at Borderview Farm owned and managed by Roger and Claire Rainville in Alburgh, Vermont (Latitude 45.0112, Longitude -73.3003, elevation approximately 120 feet).

The field consists primarily of a Benson rocky silt loam soil with an 8-to-15% slope. This soil is classified as somewhat excessively drained with low water-holding capacity. The lower portion of the field is a Covington silty clay loam, a poorly drained soil. The switchgrass stand was planted in May 2007. By 2009, in its third year of production, the stand was considered to be mature with a dense stand, and fairly clean of weeds. The stand was fertilized in late May with 50 pounds of nitrogen per acre. It was mowed only once, at full maturity in October, and the windrows were allowed to stay in the field for about four weeks before being harvested using conventional farm equipment for small, square 40-pound bales.

The reed canarygrass hay came from a 30-by-500 foot strip along the western edge of a field of 'Palaton' reed canarygrass, located on the same farm near the switchgrass stand. The soil in this part of this field is a Covington silty clay loam with 0-to-3% slope. The stand was approximately 10-to-12 years old, fairly pure in reed canarygrass. The only fertility treatment in 2009 was an application of liquid manure at a rate of approximately 5,000 gallons per acre applied in early May. The strip managed for this project was not mowed until October and, like the switchgrass, was not baled for another three-to-four weeks after mowing.

The mulch hay was a late-cut hay (mid July) from a field in Shelburne, Vermont on the Meach Cove Trust land (Latitude 44.3541, Longitude -73.2635, elevation approximately 200 feet). The primary soils are a Stockbridge and Nellis stony loam, well drained, 3-to-8% slope. No fertilizer or manure had been applied to this field in 2009. The mulch hay consisted of a mixture of orchardgrass (*Dactylis glomerata*), smooth bromegrass (*Bromus inermis*), reed canarygrass, timothy (*Phleum pratense*), red clover (*Trifolium pratense*), and white clover (*Trifolium repens*).

Twenty-five 40-pound square bails of each of the three types of hay were sourced and transported from the farms to Vermont Wood Pellet Company.

Switchgrass field at Borderview Farm, September 2009.

GRASS PELLET PRODUCTION

PRE-PROCESSING

Once the 40-pound hay bales were received at the Vermont Wood Pellet (VWP) Company mill, the grasses needed to be processed in preparation for eventual pelletization.

In addition to the main pellet production line at the facility, VWP also owns test pellet production equipment used for manufacturing and testing different blends and for pelleting process control. This smaller line was used for producing the 13 varieties of grass pellets.

Their test production line consists of a small hammermill, a small rotary drum drier, and a 400-pound per hour pellet mill. Before the grasses could be put directly into the hammermill, however, the grass bales needed to be broken and pre-chopped so that long grass strands would not jam the hammermill.

Pellet mill operators are well versed in the various material handling methods of making pellets from sawdust, woodchips, and even tree-length roundwood. Pellets made from grass are not common and therefore industry-wide material handling best practices do not exist for pre-processing grass for pellet making.

In order to pre-chop the hay several methods were explored and it was decided that a hay mulcher/blower unit would be the best option (shown in the picture below). This particular piece of equipment is designed for landscaping and allows bales of hay to be fed into a chain flail chopping chamber and then blown out of the chamber via a 6-inch diameter flex-hose.

The system is designed to blow the chopped hay onto the ground as mulch, but for this project the chopped grass was discharged into a makeshift 20-foot by 30-foot holding bin, lined with a poly-woven tarp. Large bulk sacks that are used to store grain and other commodities were then shovel filled with the chopped grass.

This process was very labor-intensive, messy, and required the use of protective clothing, eyewear, ear protection, and dust masks (as is shown in the picture below).

Left to right: A skid-mounted hay mulcher/blower was used to pre-process grass prior to pelletizing; grass is de-baled and fed to mulching unit (chopped hay was difficult to load directly into containers due to the high-velocity air flow from the discharge hose).

From top clockwise: inside of the hay bale mulcher/blower unit; a tractor-mounted, PTO-driven hammermill was used to re-grind grass fibers prior to pelletization; grass after using the bale mulcher and hammermill.

GRINDING

Chopping the hay as described above produced a considerably shorter fiber length than unprocessed grass fibers; however, it was still too coarse to make pellets. Therefore, a tractor mounted- and power take off (PTO) driven-hammer mill was used to further reduce particle size for pelletizing (see picture above lower left).

Pre-chopped hay was manually fed from the bulk storage sacks into the hammermill where the resulting finer material was collected for further blending before pelletization. Like the pre-chopping of the hay bales, re-grinding the grasses with the hammermill was very labor-intensive, messy, and required the use of protective clothing, eyewear, ear protection, and dust masks.

GRASS PELLET PRODUCTION *(cont'd)*

BLENDING

After the grass fiber had been processed (chopped and reground), the grass fibers were then batched according to the sample sizes needed for each blend. During this time the wood fiber component of each blend was also processed. To reduce the overall moisture content of the grass blends (instead of drying grass further using a rotary drum drier), pre-dried wood fiber (predominantly white pine) was used to effectively lower the moisture content of the grass/wood blends. Without any dry wood fiber, the 100% grass pellet blends contained higher moisture levels.

The prescribed amounts of grass and wood fibers were blended on a dry weight basis and although the materials were blended exactly, it is very important to note that wood fibers and grass fibers behave differently and absolute uniformity of blend is extremely difficult to achieve; meaning that while exact amounts of each material were blended in each batch, it is highly unlikely that there was the exact desired ratio of grass and wood fiber in each and every pellet made, especially for the 6% pellets. Additionally, 1% corn starch by weight was added to act as a binding agent. While possibly not an essential component, the added corn starch ensured that the blends would bind properly and form a good quality pellet. This added assurance was especially important due to the small batch sizes being produced. The table below shows the composition of each blend.[4]

Composition of each grass blend used for testing.

Sample	Amount of Grass (lbs.)	Amount of Wood (lbs.)	Amount of Binder	Total (lbs.)
Control (100% Wood)	0	500	0	500
S1 (100% Switchgrass)	500	0	5	505
S2 (25% Switchgrass)	125	375	5	505
S3 (12% Switchgrass)	60	440	5	505
S4 (6% Switchgrass)	30	470	5	505
R1 (100% Reed Canarygrass)	500	0	5	505
R2 (25% Reed Canarygrass)	125	375	5	505
R3 (12% Reed Canarygrass)	60	440	5	505
R4 (6% Reed Canarygrass)	30	470	5	505
M1 (100% Mulch Hay)	500	0	5	505
M2 (25% Mulch Hay)	125	375	5	505
M3 (12% Mulch Hay)	60	440	5	505
M4 (6% Mulch Hay)	30	470	5	505

PELLETIZING

After batching, the wood, grass, and starch components were mixed together to produce the specified percentages and then they were run through the 6mm diameter ring die pellet mill. The pellets produced were then cooled, screened to remove fines, and bagged into 40-pound plastic bags. Prior to bagging test pellets into 40-pound sacks, numerous 1-gallon samples of each blend were gathered for laboratory analysis.

Grass fiber alone does not flow very well and tends to bridge and ball up very easily during the pelletization process. This added to the mechanical challenges of producing a 100% grass pellet. Also, the pellets produced with 100% grass tended not to be as well formed as the wood/grass blend pellets. This can be attributed to the low levels of lignin in the material as well as the higher moisture content of the grass fibers.

From top: VWP staff testing moisture content of fibers prior to pelletizing grass samples; the test pellet production mill used at VWP; blended material being passed through a 6mm-diameter ring die to form the pellet fuel.

GRASS PELLET QUALITY AND ANALYSIS

IMPORTANCE OF PELLET QUALITY

For a pellet to be suitable for general distribution into the established pellet fuel heating market, it should conform to set standards of quality. Quality pellets are a clean, consistent, and uniformly-sized fuel that ensure fewer mechanical fuel feeding jams, less ash produced (and therefore less time spent on removal), and longer periods of maintenance-free burn time for stoves, furnaces, and boilers.

The Pellet Fuels Institute (PFI) is a national organization that promotes the use of pellet fuels and has established standards governing the quality of pellet fuels sold on the market. Typically these parameters apply to wood pellets because that is the primary pellet fuel in use at this time, but any fuel pellet on the market should meet these quality standards.

The following table illustrates the pellet fuel quality parameters for the four main grades of pellet fuels as designated by PFI.

PFI Pellet Fuel Quality Parameters

	Likely Source Materials	Size	Moisture Content	Btu Value	Ash Content	Bulk Density	Fines Content	Chloride (ppm)
Super Premium	Wood fiber	6-8mm	<6%	>8,000 Btu/lb.	<0.5%	40-46lbs./ft^3	<0.5%	<300
Premium	Wood fiber	6-8mm	<8%	>8,000 Btu/lb.	<1.0%	40-46lbs./ft^3	<0.5%	<300
Standard	Primarily wood fiber with possibly a small percent of other ag fiber	6-8mm	<8%	>8,000 Btu/lb.	<2.0%	38-46lbs./ft^3	<0.5%	<300
Utility or Industrial	Wood fiber, bark, grass, other	6-8mm and larger	<10%	>8,000 Btu/lb.	<6.0%	38-46lbs./ft^3	<0.5%	<300

PELLET FUEL QUALITY STANDARDS

Size. Fuel pellets are of uniform size and shape (between 1 or 1-1/2 inches in length by approximately 1/4-5/16 inches in diameter), making them easy to store and use in fuel auguring systems. Pellets also take up much less space in storage than other biomass fuels because they are relatively dry and densified compared to other biomass fuels such as woodchips.

Moisture Content. Pellets typically have moisture content between 4 and 6%. If pellets are stored improperly and are remoistened, many issues are created.

Energy Content (Btu Value). Pellets have a higher energy content by weight (roughly 8,084 Btu per pound at 6% moisture content) than woodchips (roughly 4,500 – 5,000 Btu per pound at 50% moisture) and other non-densified biomass fuels. Pellets should contain a minimum of 8,000 Btu per dry pound.

Ash Content and Mineral Composition. Ash content is perhaps the greatest distinguishing parameter among the four grades of pellet fuels. Super premium pellets have less than 0.5% ash content; premium pellets, less than 1%; standard pellets, between 1-2%; and utility or industrial pellets have 2-6%. The amount and composition of minerals in the fuel will determine the amount of ash produced and to what extent these minerals will fuse or melt together, forming clinkers during combustion at standard combustion temperatures.[5]

Density. Pellets have consistent hardness and energy content (minimum 40 pounds per cubic foot for premium or super premium). Density is a key factor in pellet fuel quality. Less dense pellets will burn less efficiently and deliver less heat. Less dense pellets are also less durable and often degrade into fines prematurely.

Fines. There is commonly a small amount of fines or dust from pellet breakdown due to wear and tear in handling and shipping. Excessive fines content can cause material bridging in the fuel hopper; minimizing the amount of fines content avoids fairly serious problems with the fuel feeding systems. The amount of fine dust passing through 1/8-inch screen should be no more than 0.5% by weight.

Chlorides. There should be limited salt content (no more than 300 parts per million) in pellets. When pellets are burned, chloride gases are extremely corrosive to metal and excessive levels can cause significant damage to heat exchange and exhaust venting systems.[6]

For a pellet to be suitable for general distribution into the established pellet fuel heating market, it should conform to set standards of quality.

GRASS PELLET QUALITY AND ANALYSIS *(cont'd)*

PELLET FUEL LABORATORY ANALYSIS RESULTS

Once the three grass types were blended into four different grass concentrations and pelletized, composite samples of the resulting pellets were gathered at VWP's facility in one-gallon zip-top plastic bags. These were shipped to Twin Ports Testing, Inc. based in Superior, Wisconsin.

Proximate and ultimate analyses were conducted[7] in an effort to assess how the grasses, at 100%, 25%, 12%, and 6% concentrations, compared to a typical pellet of 100% wood. The results of this testing gave insight to fuel performance during the combustion trials.

Twin Ports Testing, Inc. conducted tests for the parameters (shown in the table below) that were then used to compare the grass pellets to the control wood pellet. All of the results were based on the weight of the sample unless otherwise specified:

Ultimate Analysis	Proximate Analysis
Moisture Content	Carbon
Ash Content	Hydrogen
Volatile Matter	Oxygen
Fixed Carbon	Nitrogen
Energy Value	Sulfur

In addition to the ultimate and proximate analyses, samples were also tested for chlorine content and to determine the temperature at which the ash in the fuel would fuse together. The following sections of this report present the results of this analysis and discuss their significance.

Moisture Content

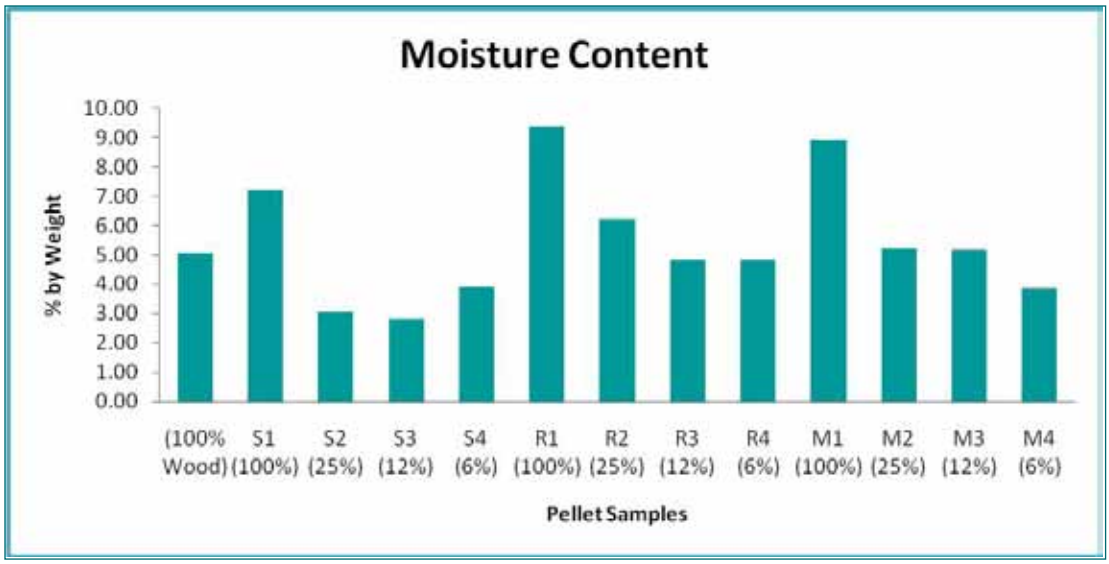
Moisture content is an extremely important fuel quality parameter when it comes to green wood fuels such as cordwood and woodchips. For pellets made of dried materials, however, its importance is less significant, though a slight difference in moisture can impact fuel quality and performance. Therefore, moisture content was one component of the laboratory analysis. The PFI standard for moisture content requires less than 8% for premium-grade pellets and less than 6% for super premium-grade pellets. The table and bar graph on the next page show the measured moisture content for the various blends.

The results show relatively little fluctuation in moisture content across the various blends tested and where there is fluctuation it does not represent differences in the source material itself—merely that certain samples were dried slightly more or less than the others.

It should be noted that the grasses were not actively dried prior to pelletization. The three 100% grass pellets (S1, R1, and M1) had the highest moisture content of all the samples, while the grass pellet samples blended with wood fiber had lower moisture contents due to the fact that the wood fiber had been dried to moisture content below 5%.

If grass were to be successfully pelletized and sold into the pellet fuel market, these pellets would need to meet the same quality standards as wood pellets, including moisture content. Therefore, the grass would need to be dried slightly more than was done during this test. While the R1 and M1 pellet samples exceeded the 8% moisture content cut off for Standard grade, they did meet the criteria for Utility grade pellets. It should be noted again that the moisture content of source pellet fiber can easily be adjusted by either more or less drying.

Sample	Moisture Content
Control (100% Wood Pellet)	5.07%
S1 (100% Switchgrass Pellet)	7.21%
S2 (25% Switchgrass Pellet)	3.06%
S3 (12% Switchgrass Pellet)	2.81%
S4 (6% Switchgrass Pellet)	3.89%
R1 (100% Reed Canarygrass Pellet)	9.37%
R2 (25% Reed Canarygrass Pellet)	6.22%
R3 (12% Reed Canarygrass Pellet)	4.83%
R4 (6% Reed Canarygrass Pellet)	4.82%
M1 (100% Mulch Hay Pellet)	8.90%
M2 (25% Mulch Hay Pellet)	5.22%
M3 (12% Mulch Hay Pellet)	5.17%
M4 (6% Mulch Hay Pellet)	3.85%



GRASS PELLET QUALITY AND ANALYSIS *(cont'd)*

Ash Content

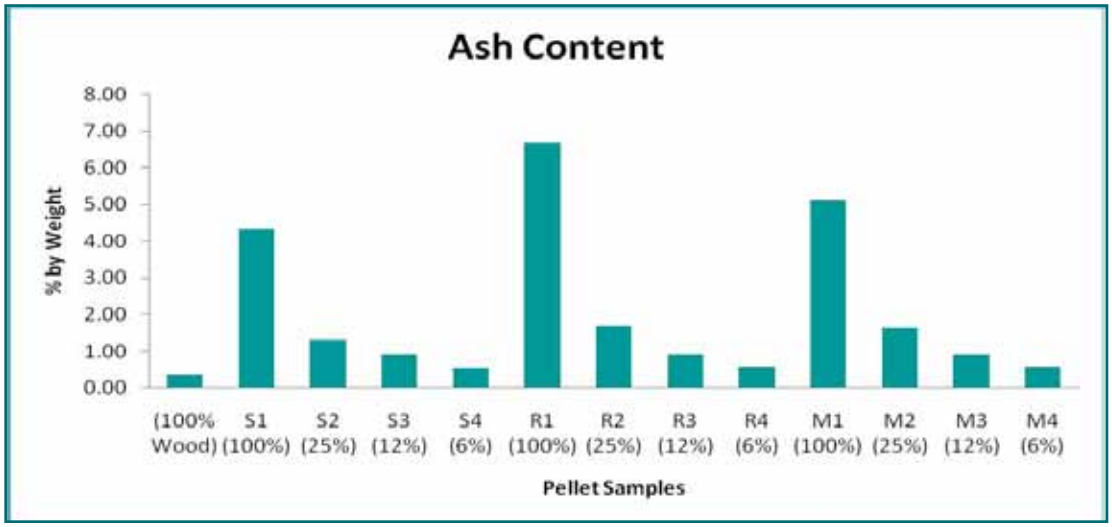
Ash content is a critically important variable in determining a pellet fuel's overall quality. High ash content pellets are more difficult to combust and present more challenges to the combustion system's operation. Of course, as was stated previously in this report, ash content is a primary concern in the use of grass pellets as a fuel. The higher nutrient content in grasses translates to high ash content. The PFI standards for pellet quality require less than 0.5% ash content for super premium, less than 1% ash for premium, less than 2% for standard, and less than 6% for utility-grade pellets. The table (at left) shows the measured ash content of the various blends and the graph below compares the ash content of each of the blends tested here.

Sample	Ash Content
Control (100% Wood Pellet)	0.35%
S1 (100% Switchgrass Pellet)	4.32%
S2 (25% Switchgrass Pellet)	1.31%
S3 (12% Switchgrass Pellet)	0.91%
S4 (6% Switchgrass Pellet)	0.55%
R1 (100% Reed Canarygrass Pellet)	6.67%
R2 (25% Reed Canarygrass Pellet)	1.69%
R3 (12% Reed Canarygrass Pellet)	0.90%
R4 (6% Reed Canarygrass Pellet)	0.56%
M1 (100% Mulch Hay Pellet)	5.12%
M2 (25% Mulch Hay Pellet)	1.63%
M3 (12% Mulch Hay Pellet)	0.90%
M4 (6% Mulch Hay Pellet)	0.56%

The results clearly show that the blended pellets containing the most wood fiber have the lowest ash content. The control sample (100% wood fiber pellet) meets the PFI standard for super premium. Of the three 100% grass pellets, reed canarygrass has the highest ash content, whereas switchgrass had less than 5% ash content and mulch hay falls in between the two. The 100% switchgrass and the 100% mulch hay pellets would meet the PFI standard for utility-grade pellets, however, reed canarygrass had too much ash to even meet this standard. All the 25% grass blends meet the standard grade for ash content while all the 12% and 6% blends meet the premiumn grade due to the high concentrations of wood fibers.

Ash Fusion Temperature – Reducing Atmosphere

Understanding the total ash content of a fuel is important but knowing how ash minerals will behave under combustion conditions is critical. This test helps determine the combustion temperature at which the minerals (ash) in the pellet will fuse or bind into clinkers—similar to how sand forms into glass at extreme tempera-



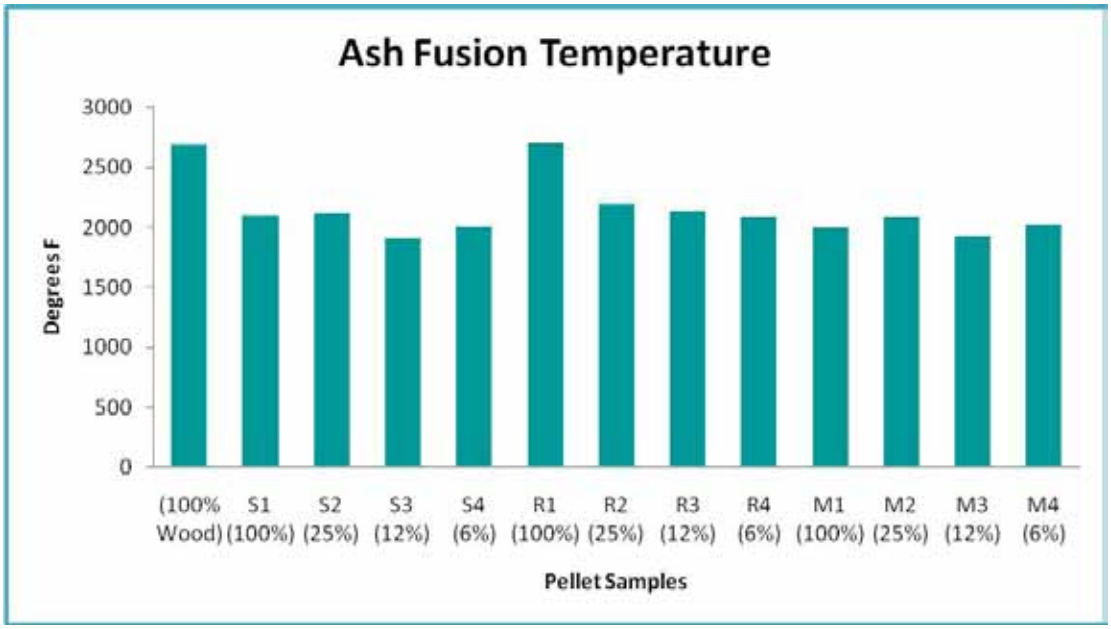
tures. Ash fusion temperature is an extremely important test because it indicates how likely it is that "clinkers" (fused ash) will form under combustion conditions.

The type and composition of mineral material greatly impacts whether clinkers will form. Alkali and silica minerals in biomass feedstock increase the likelihood of ash slagging, fouling, and agglomeration during combustion.[8] Both high-fusion temperature and proper air-to-fuel ratio calibration can help reduce formation of clinkers and fusion of ash on the fuel grate and heat transfer surfaces. Fuel with lower ash fusion temperature (than wood) is likely to create combustion performance and maintenance issues.

There is no PFI standard for ash fusion temperature. The table (above right) shows the temperature at which minerals were found to fuse into clinkers and the graph below compares the ash fusion temperatures across all of the blends tested here. As illustrated, of the 100% grass blends, mulch hay has the lowest ash fusion temperature, followed closely by switchgrass, whereas 100% reed canarygrass has almost the same fusion temperature as 100% wood. If this were the only performance criteria, the laboratory results shown here suggest that when these fuels are burned, the 100% reed canarygrass pellet fuels will perform on par with the 100% wood pellet and present the least amount of additional system maintenance.

Sample	Ash Fusion Temp.
Control (100% Wood Pellet)	2,690° F
S1 (100% Switchgrass Pellet)	2,095° F
S2 (25% Switchgrass Pellet)	2,120° F
S3 (12% Switchgrass Pellet)	1,910° F
S4 (6% Switchgrass Pellet)	2,000° F
R1 (100% Reed Canarygrass Pellet)	>2,700° F
R2 (25% Reed Canarygrass Pellet)	2,190° F
R3 (12% Reed Canarygrass Pellet)	2,140° F
R4 (6% Reed Canarygrass Pellet)	2,090° F
M1 (100% Mulch Hay Pellet)	1,995° F
M2 (25% Mulch Hay Pellet)	2,090° F
M3 (12% Mulch Hay Pellet)	1,930° F
M4 (6% Mulch Hay Pellet)	2,020° F

Upon closer examination, there seems to be some inconsistency in the results if looked at purely from a temperature aspect. The ash fusion temperatures of the various grass blends



GRASS PELLET QUALITY AND ANALYSIS *(cont'd)*

In order to successfully integrate grass fiber into commercially viable pellet fuel for heating, sulfur content should be kept below 0.02%.

should not be as low as the ash fusion temperature of 100% grass because they are heavily blended with wood fiber which has a higher fusion temperature. As the amount of wood fiber is increased in the switchgrass and mulch hay pellets, the fusion temperature should theoretically increase. Also, the ash fusion temperature of 25% reed canarygrass (R2) should not be 2,190° F, when it is >2,700° F for 100% reed canarygrass (R1) and 2,690° F for 100% wood (control sample). Possible reasons for the unexpectedly low ash-fusion temperatures observed in the 25%, 12%, and 6% reed canarygrass pellets could be that the wood fiber did not distribute as evenly throughout during blending and samples analyzed by the laboratory were not representative of the blend.

Another important point that will be discussed in further detail in the Operational Combustion Trials section is that during the operational test burns clinker formation was prevalent at much lower temperatures (800-1600° F) than reported by the laboratory results presented here. This may be attributable to, in part, the difference between laboratory procedures to determine the upper limits of ash fusion thresholds and "real world" combustion where even partial fusion can happen and present issues at lower temperatures.

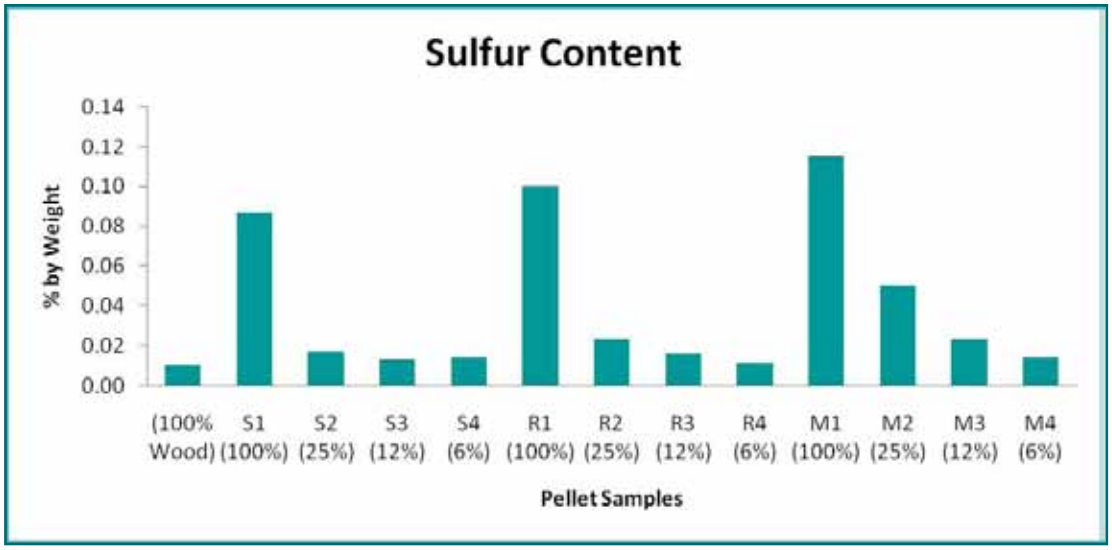
For each fuel type there is an optimum burner box temperature that allows efficient combustion while minimizing clinker formation. Making adjustments to find the optimum temperatures is difficult given the constant fluctuations in the heat load. It is easier therefore, to fine-tune when test burns are conducted over longer time periods than were allowed for in these tests.

Sulfur

Sulfur content is an extremely important quality parameter for a number of reasons. Sulfur in fuel, when combusted, produces sulfur oxides (SO_X) which are acid rain causing chemicals. Secondly, sulfur oxides can be corrosive to combustion equipment. Wood typically has low sulfur content. Although no PFI standard exists for sulfur content, in order to successfully integrate grass fiber into commercially viable pellet fuel for heating, sulfur content should be kept below 0.02%. The table below shows the measured sulfur content of the blends tested here and the graph on the next page compares the sulfur content of each.

The control blend (100% wood) had the lowest concentrations of sulfur. Among the grass pellet samples, the 100% switchgrass had the lowest concentration among the 100% grass pellets (compared to R1 and M1) but still an order of magnitude higher than the control wood pellet. The mulch hay had the highest concentrations of sulfur and even the M2, M3, and M4 con-

Sample	Sulfur Content
Control (100% Wood Pellet)	0.01%
S1 (100% Switchgrass Pellet)	0.09%
S2 (25% Switchgrass Pellet)	0.02%
S3 (12% Switchgrass Pellet)	0.01%
S4 (6% Switchgrass Pellet)	0.01%
R1 (100% Reed Canarygrass Pellet)	0.10%
R2 (25% Reed Canarygrass Pellet)	0.02%
R3 (12% Reed Canarygrass Pellet)	0.02%
R4 (6% Reed Canarygrass Pellet)	0.01%
M1 (100% Mulch Hay Pellet)	0.12%
M2 (25% Mulch Hay Pellet)	0.05%
M3 (12% Mulch Hay Pellet)	0.02%
M4 (6% Mulch Hay Pellet)	0.01%



tained considerable amounts of sulfur. As can be seen with these results, as more wood fiber is added to the grass pellets the sulfur content lowers thereby making the blended grass pellet more similar in sulfur content to the control 100% wood pellet. (In the case of mulch hay, however, which was found to have higher sulfur content than the other grasses, it was only the pellet with the lowest concentration of grass content that approached sulfur content similar to the control 100% wood pellet.)

Energy Content

Two of the primary advantages to pellet fuels are lower moisture content (pellets have much lower moisture contents than green fuel like woodchips) and the pellet's bulk density (pellets weigh more per volume than light and loose materials like sawdust)—both affecting the energy content. To ensure quality pellet fuel, the PFI standard calls for more than 8,000 Btu per dry pound. The table at right shows the measured energy content of each of the blends tested and the bar graph on the next page illustrates a comparison of each.

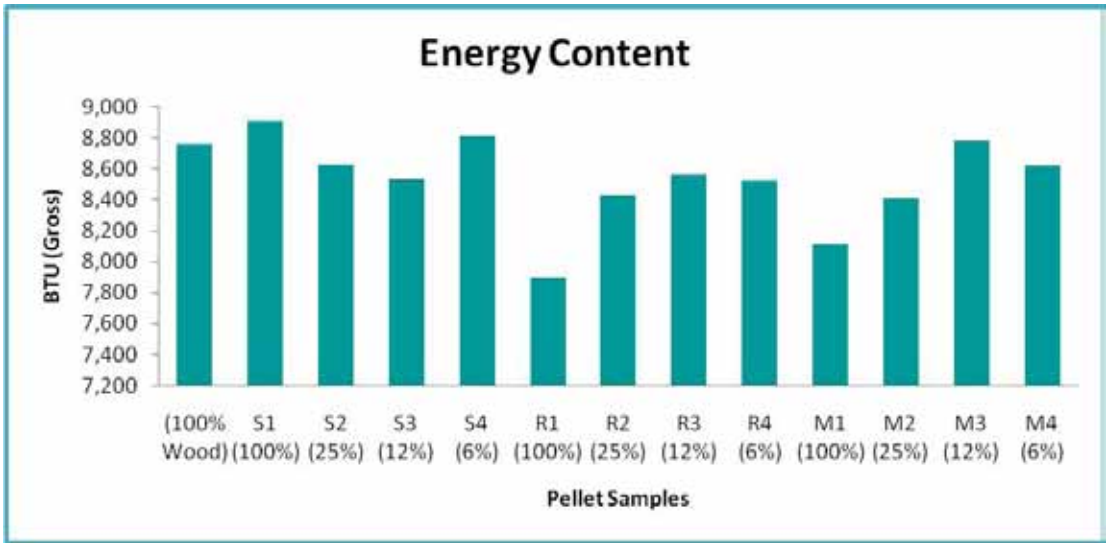
It is clear that both the 100% reed canarygrass and the 100% mulch hay samples have considerably lower energy values than both the control 100% wood pellet and the grass/wood blends, especially those blends containing higher percentages of wood fiber. Nevertheless, the 100% switchgrass sample breaks that pattern with a higher energy value than both

Sample	Btu/ dry lb.
Control (100% Wood Pellet)	8,759
S1 (100% Switchgrass Pellet)	8,908
S2 (25% Switchgrass Pellet)	8,627
S3 (12% Switchgrass Pellet)	8,529
S4 (6% Switchgrass Pellet)	8,811
R1 (100% Reed Canarygrass Pellet)	7,900
R2 (25% Reed Canarygrass Pellet)	8,430
R3 (12% Reed Canarygrass Pellet)	8,559
R4 (6% Reed Canarygrass Pellet)	8,526
M1 (100% Mulch Hay Pellet)	8,114
M2 (25% Mulch Hay Pellet)	8,404
M3 (12% Mulch Hay Pellet)	8,783
M4 (6% Mulch Hay Pellet)	8,618

Two primary advantages to pellet fuels are lower moisture content (pellets have much lower moisture contents than green fuel like woodchips) and the pellet's bulk density (pellets weigh more per volume than light and loose materials like sawdust)—both affecting the energy content.

GRASS PELLET QUALITY AND ANALYSIS *(cont'd)*

Herbaceous plant material, such as grasses contain significantly higher levels of the mineral chlorine than is found in wood. This is an important difference since chlorine, when combusted, produces corrosive gases that can deteriorate boiler heat exchangers and the lining of the exhaust flue.



the control wood pellet and the grass/wood blends with more wood fiber content. While this data indicates switchgrass pellets have slightly higher energy value than pelletized wood, most data suggests that switchgrass pellets normally have slightly less (2-3%) than wood pellets.[9] This inconsistency does not present a problem due to the relatively slim margin of difference of energy content between the S1 and control wood pellet samples.

Upon first glance at the bar chart above, there seems to be conflicting patterns in the data. The R and M series increase in energy content with increasing wood fiber, while the S series actually declines in energy value as the amount of wood fiber increases. Since the S1 sample had a higher energy value than the control, the decreasing Btu value makes sense when more, lower energy value wood is added to the blends.

All the pellet samples analyzed met the PFI standard for energy content (greater than 8,000 Btu/dry pound) with the exception of the R1 sample.

Chlorine

Grass and wood both contain chlorine, since this is a soil micronutrient that, in small quantities, is helpful to plant growth. Herbaceous plant material, such as grasses contain significantly higher levels of the mineral chlorine than is found in wood. This is an important difference since chlorine, when combusted, produces corrosive gases that can deteriorate boiler heat exchangers and the lining of the exhaust flue. The PFI standard for chloride is <300 parts per million (ppm). The table and graph on the following page show the measured chlorine content for each of the blends tested and comparison of each. (Please note that, when discussing a fuel's characteristics, the terms "chloride" and "chlorine" are used interchangeably; therefore, these results showing chlorine content of the fuels tested here can be directly compared to the PFI standard for chloride.)

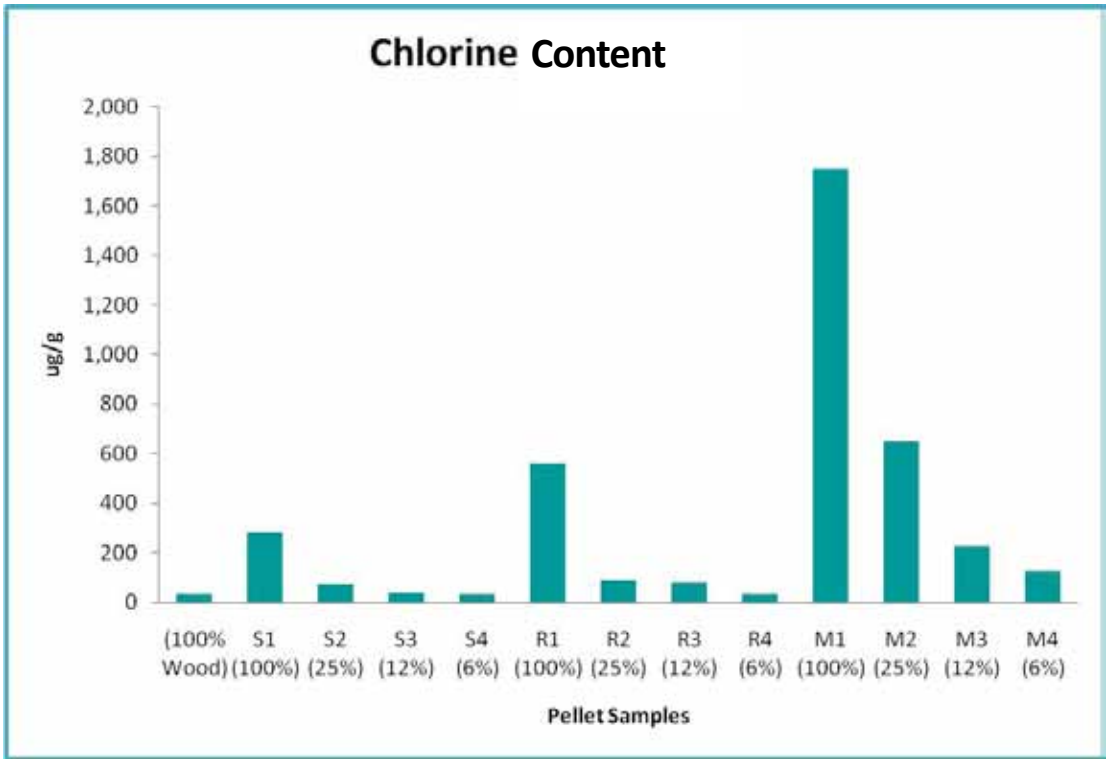
The results show dramatically higher levels of chlorine in the three 100% grass pellet samples—especially the mulch hay. While the switchgrass pellet contained the lowest concentration of chlorine of the 100% grasses, it was still much higher than the wood control sample.

Sample	Chlorine Content (ppm)[10]
Control (100% Wood Pellet)	32
S1 (100% Switchgrass Pellet)	279
S2 (25% Switchgrass Pellet)	75
S3 (12% Switchgrass Pellet)	36
S4 (6% Switchgrass Pellet)	33
R1 (100% Reed Canarygrass Pellet)	562
R2 (25% Reed Canarygrass Pellet)	90
R3 (12% Reed Canarygrass Pellet)	81
R4 (6% Reed Canarygrass Pellet)	33
M1 (100% Mulch Hay Pellet)	1,752
M2 (25% Mulch Hay Pellet)	649
M3 (12% Mulch Hay Pellet)	228
M4 (6% Mulch Hay Pellet)	126

The PFI threshold for chloride is <300 ppm so all the switchgrass pellets, and only the R2, R3, and R4, and the M3 and M4 pellets would meet this standard. Pellets containing higher than 300 ppm of chloride present an unacceptable risk of corrosion to combustion heating equipment. Specifically, the 100% reed canarygrass (R1) and higher-content mulch hay (M1 and M2) samples would not meet the PFI standard for chloride.

Concentrations of chlorine in the grasses may be influenced by field fertilization practices as well as annual growth/harvest cycles. Chlorine concentrations might be minimized by changing field fertilization practices, harvesting crops later in the year, and possibly extending the timeframe between mowing and harvesting.

Concentrations of chlorine in the grasses may be influenced by field fertilization practices as well as annual growth/harvest cycles.

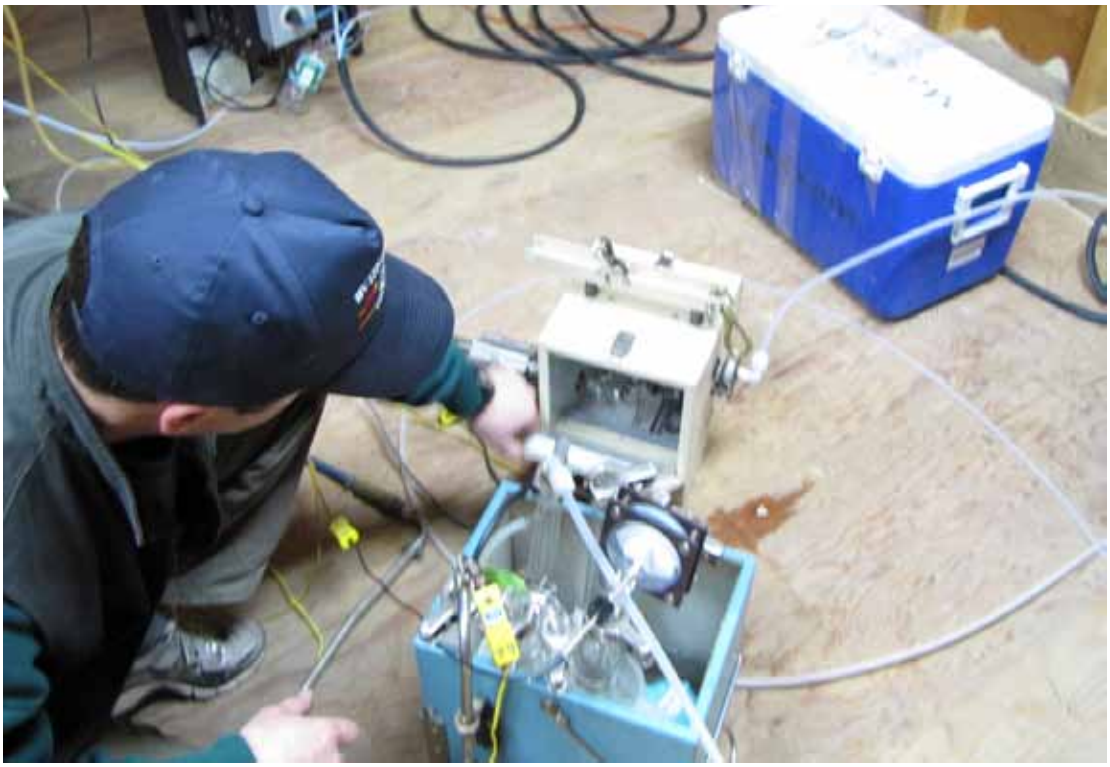


STACK EMISSIONS TESTING

When any boiler fuel (biomass or traditional liquid fossil fuel) is combusted, a wide range of pollutants are emitted from the system's exhaust stack. Given the body of information on the physical and chemical fuel properties of wood and the extensive body of data on wood fuel combustion emissions, there is a solid understanding of how wood fuel properties can impact the corresponding air emissions. For grass as a combustion fuel, however, there is less data available and the link between the fuel properties of grass and the resulting emissions is not as well understood.

For this reason, complete stack emissions testing was conducted as part of this study. Gammie Air Test Monitoring LLC, based in West Simsbury, Connecticut, was hired to conduct stack emissions testing for the three 100% grass pellet varieties and the control wood pellet fuel. These emissions tests were conducted on March 11-12, 2010. While several other stack emissions such as carbon monoxide were also monitored, particulate matter and oxides of nitrogen were the focus.

All stack emissions testing was conducted on the 500,000 Btu/hour Solagen boiler that has no additional emission control technology between the boiler and the stack. All emissions measurements gathered by Gammie Air for this project were conducted and reported according to US Environmental Protection Agency (EPA) prescribed methodology.[11]



John Gammie of Gammie Air Test Monitoring prepares equipment prior to emissions testing.

CARBON MONOXIDE

Carbon monoxide (CO) is produced from the partial oxidation of carbon-containing compounds; it forms when there is not enough oxygen to produce carbon dioxide (CO_2) such as during incomplete combustion. While CO is extremely dangerous to humans if improperly vented and allowed to build up indoors, it is not an environmental pollutant when properly dispersed into the atmosphere. CO is, however, an indicator of other pollutants such as volatile organic compounds (VOC) and others produced as a result of incomplete combustion. It is for this reason that CO is commonly monitored and scrutinized by air quality regulators. Under new draft rules proposed by EPA, CO levels for solid fueled boilers would need to be below 160 ppm when operating at 7% oxygen levels.[12]

CO was measured for each of the pellet fuel test burns, both stack emissions testing and the operational test burns. CO emissions do not necessarily reflect on the quality of the pellet fuel, rather they indicate how well the system is performing given its numerous settings. The measured CO emissions for each of the 100% blends (wood, switchgrass, reed canarygrass, and mulch hay) are shown in the table above right.

Sample	CO Emissions (ppm)
Control (100% Wood)	7.5
S1 (100% Switchgrass)	2.7
R1 (100% Reed Canarygrass)	5.8
M1 (100% Mulch Hay)	31.6

The three tests for the 100% grass pellets and the fourth set performed on the 100% wood control illustrate the different quantities of released CO in each of the test burns conducted for stack emissions testing (please see the appendix for full results of this testing). While the wood, switchgrass, and reed canarygrass combustion conditions were excellent, the mulch hay combustion conditions were not quite as good. Mulch hay pellets proved to be a rather difficult fuel in terms of the ability to properly calibrate the system controls to readily achieve ideal combustion conditions for the test burns. It is important to note that the CO levels listed above were measured during the stack emissions testing performed by Gammie Air, and the combustion systems were operating at full load capacity. Therefore the CO levels were considerably lower than would be expected under more variable heat load conditions. Further examination of CO levels during "real world" operating conditions can be found in the Operational Combustion Trials section of this report.

CO emissions do not necessarily reflect on the quality of the pellet fuel, rather they indicate how well the system is performing given its numerous settings.

STACK EMISSIONS TESTING *(cont'd)*

Particulate matter emissions generally are classified into two basic categories—coarse and fine particulates. Coarse PM is typically measured as total PM whereas fine particulates are measured as PM10 or particulates smaller than 10 microns in size.

PARTICULATE MATTER

Particulate matter (PM) is a complex mixture of very small particles and even liquid droplets. PM emissions from combustion are made up of a number of components, including acids (such as nitrates and sulfates), organic chemicals, metals, and soil or dust particles. Some particles, such as dust, dirt, soot, or smoke, are large or dark enough to be seen with the naked eye. Other particles are so small they can only be detected using a microscope.

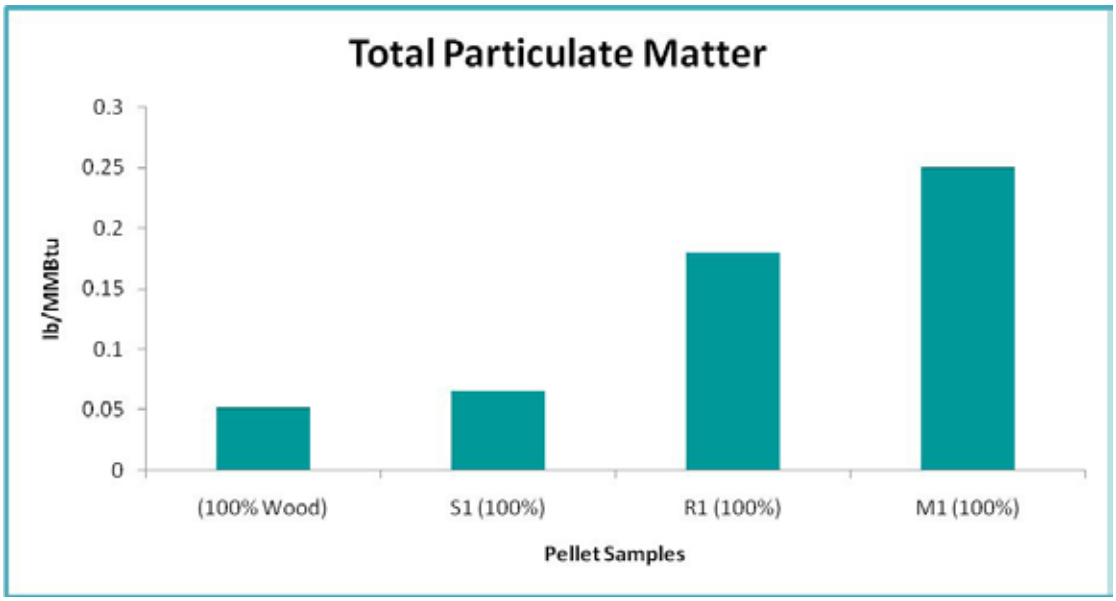
Particulate matter emissions generally are classified into two basic categories—coarse and fine particulates. Coarse PM is typically measured as total PM whereas fine particulates are measured as PM10 or particulates smaller than 10 microns in size. All PM can pose a human respiratory health problem, but fine particulates pose a much greater health risk.

Methods of particulate control vary for different types and sizes of boilers. The most basic method of reducing PM emissions is using an efficient combustion technology and proper system operation and maintenance. In addition, supplemental, post-combustion or "back-end" control technologies can be utilized. For large utility-scale boilers, electrostatic precipitators (ESP), scrubbers, and baghouses are commonly utilized. For medium-sized institutional and commercial boilers, mechanical devices such as cyclones can be used with less effectiveness on controlling fine particulates. In many cases, an effective method is to utilize low ash content fuels. The table (above right) shows the results from total particulate emissions testing by Gammie Air at Meach Cove Trusts's 500,000 Btu/hour system employing no back-end emission control technology. The graph on the next page compares the results across the blend samples tested.

Sample	Total Particulate Emissions (lbs./MMBtu)
Control (100% Wood)	0.052
S1 (100% Switchgrass)	0.066
R1 (100% Reed Canarygrass)	0.18
M1 (100% Mulch Hay)	0.25

The results illustrate the basic correlation between the ash content of the fuel and the resulting PM emissions. Those fuels with a higher ash content yield more particulate that settles to the bottom of the combustion chamber as well as the ultra-fine fly ash that is carried up the stack. The grasses with higher ash content produced correspondingly higher levels of PM emissions. The exception to this is the M1 pellet fuel that had lower ash content than the reed canarygrass and yet produced PM emissions at a greater rate that can be attributed to the less favorable combustion conditions during the M1 pellet fuel test burn (see the higher CO levels for M1). It can be assumed that under more favorable combustion conditions, the M1 grass pellets would have produced a slightly lesser amount of PM emissions.

Air emission regulations in Vermont allow up to 0.2 pounds/MMBtu for total particulate matter.[13] The results show that all pellet fuels tested, except for the mulch hay, could meet the existing air-quality regulations without any back-end control device for PM emissions.[14] New, more stringent air-emissions limits, however, have been proposed by EPA. These new draft rules would limit PM emissions from boilers smaller than 10MMBtu/hour to 0.03 pounds/MMBtu. If implemented, even the 100% wood pellet fuel would require further control efforts to achieve this threshold.



A third category, of PM, the ultra-fine particles, are those approximately 2.5 microns in diameter and smaller.

Filterable Particulate Matter

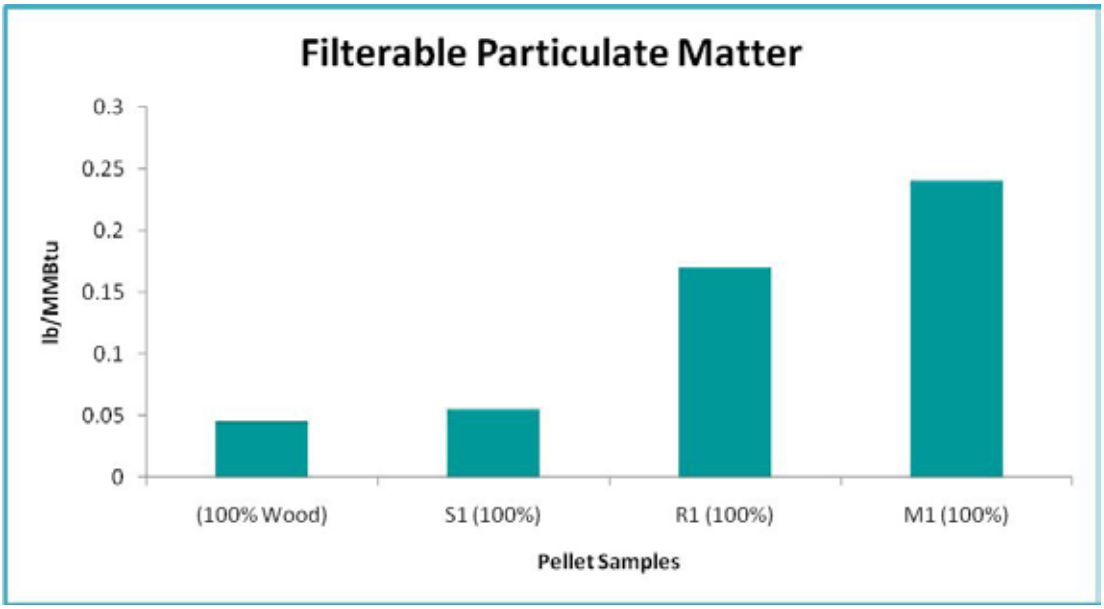
Within total PM there are coarse particles (those greater in diameter than 10 microns) and fine particles (those smaller than 10 microns in diameter). A third category, the ultra-fine particles, are those approximately 2.5 microns in diameter and smaller. Filters can be used to sample and measure the full range of PM emitted, but a significant amount of the portion of PM that is ultra fine passes right through these filters with water vapors (i.e., it is "condensable"). With solid biomass combustion, typically the filterable portion of the PM emitted is the large majority whereas the condensable portion is a very small percentage of the total. The table at right shows the results of the filterable portion of the PM sampled and measured by Gammie Air. The graph on the next page compares these results.

The pattern here was the same as the pattern from the total particulate test—when combusted, 100% wood and switchgrass pellets emitted considerably less than the reed canarygrass and mulch hay pellets. When the filterable PM results are compared against the total PM results, filterable PM accounted for 83-96% of the total amount of PM. Switchgrass pellet fuel had the lowest percentage and mulch hay pellet fuel had the highest percentage of filterable PM as compared to the total amount of PM.

Sample	Filterable Particulate (lbs./MMBtu)
Control (100% Wood)	0.045
S1 (100% Switchgrass)	0.055
R1 (100% Reed Canarygrass)	0.17
M1 (100% Mulch Hay)	0.24

STACK EMISSIONS TESTING *(cont'd)*

Fine particulates 2.5 microns and smaller are of special interest to air quality regulators because they pose the greatest overall threat to human respiratory health.



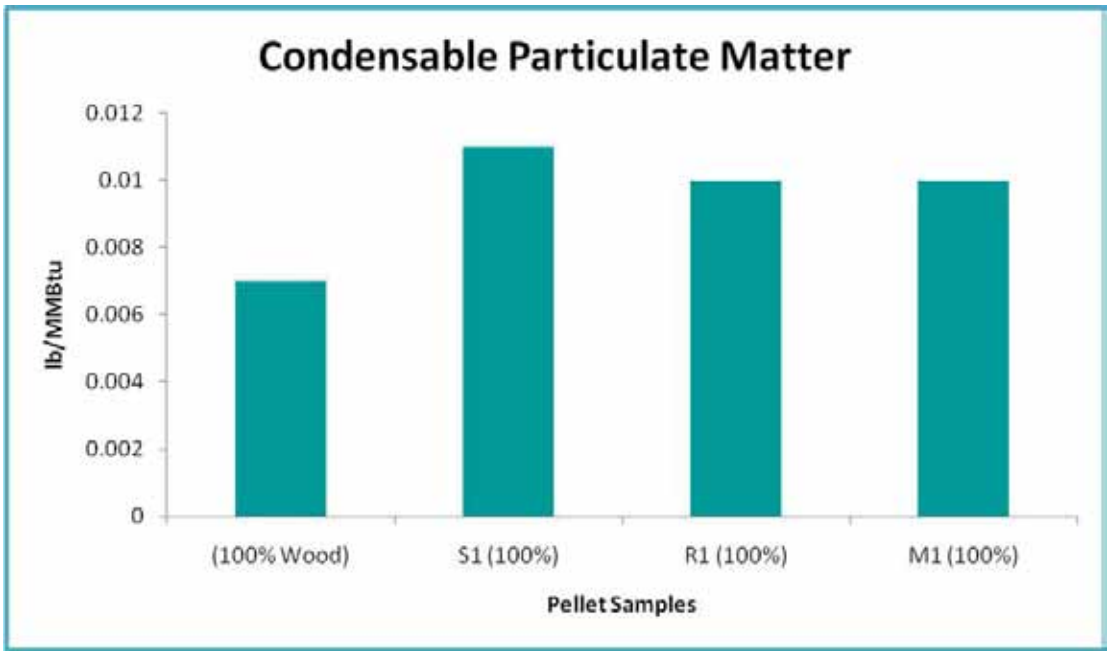
Condensable Particulate Matter

As explained above, the ultra-fine particles cannot be captured by filters in stack testing since they are predominantly bound to and transported by the water vapors in the exhaust gases. To sample and measure this particular subset of particulates, a water vapor capture and cooling process is used to determine the amount of ultra-fine particulates being emitted. Fine particulates 2.5 microns and smaller are of special interest to air-quality regulators because they pose the greatest overall threat to human respiratory health. The table at right show the results of the condensable portion of the PM as tested by Gammie Air. The graph on the next page compares these results.

The S1 pellet fuel produced the highest amount of condensable PM but the lowest total PM levels of the three grass pellet types. The S1 pellet fuel also yielded the highest percentage of condensable PM (16.7%) whereas the M1 pellet fuel produced the lowest percentage of condensable PM (4.0%). Although the ultra-fine particulates in the condensable portion of the combustion exhaust are of greatest concern, there are not, at this time, specific regulatory thresholds for these emissions. There are, however, ambient air thresholds that air-quality regulators must enforce by limiting any further emissions that would trigger higher ambient levels in a given air shed.

Sample	Condensable PM (lbs./MMBtu)
Control (100% Wood)	0.007
S1 (100% Switchgrass)	0.011
R1 (100% Reed Canarygrass)	0.01
M1 (100% Mulch Hay)	0.01

All Souls Interfaith Gathering in Shelburne, Vermont, where all combustion tests (both stack and "real world" burns) were conducted.



STACK EMISSIONS TESTING *(cont'd)*

OXIDES OF NITROGEN

Generally, the two best methods for controlling NO_x emissions are to minimize nitrogen content in the fuel combusted and to slightly lower the firebox temperature.

Nitrogen oxides (NO_X) are a broad category that includes nitric oxide (NO) and nitrogen dioxide (NO_2). Nitrogen oxide emissions contribute to particulate matter levels, smog formation, and acid rain. They are produced during combustion, especially at high temperature from fuels containing nitrogen. Although they are primarily produced from fuels containing nitrogen, they can also be produced from nitrogen in the combustion air, but only at extremely high temperatures.

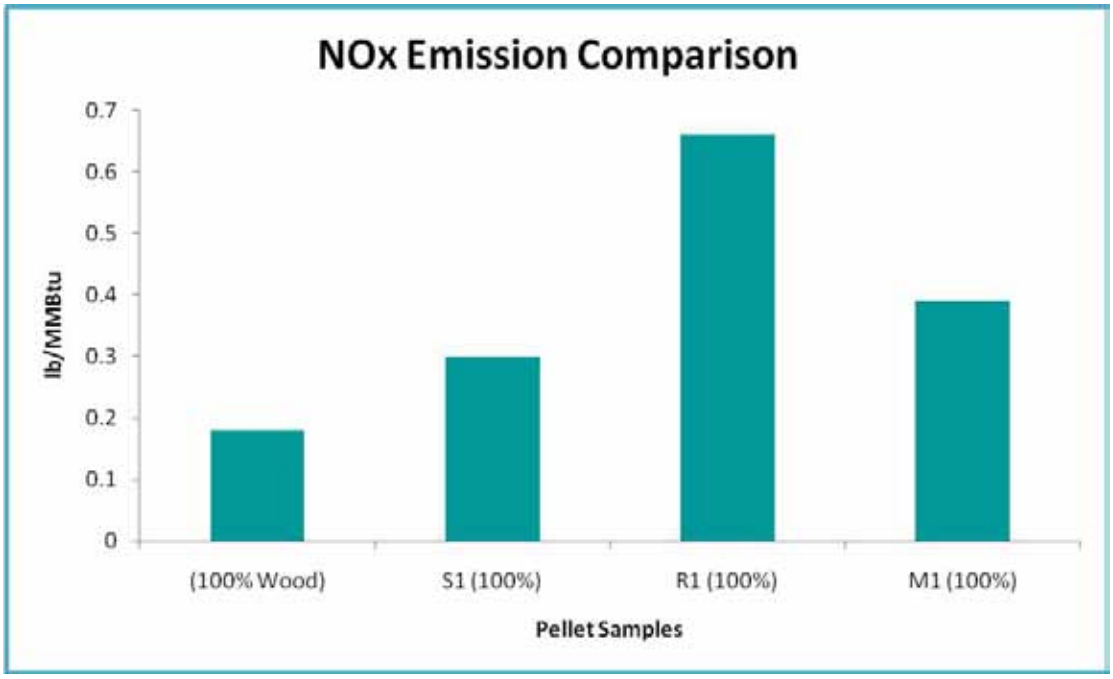
The table (above right) shows the results of pellets sampled during the emissions testing at Meach Cove Trust's 500,000 Btu/hour boiler system with no back-end NO_X control technology. The graph on the next page compares these results and illustrates that the grass blends produce NO_X emissions at a greater rate than the control wood pellet, with reed canarygrass having the highest NO_X emissions rate among the three grass blends tested here.

When the NO_X emissions data is compared to the measured nitrogen content of the pellet fuel, there is an interesting pattern. In the pellet fuel, switchgrass contained the highest concentrations of nitrogen, yet has the lowest NO_X emissions rate among the grasses tested here; mulch hay pellets contained the second highest levels of nitrogen, but produced the second lowest emissions rate of NO_X; and reed canarygrass pellets contained the lowest concentrations of nitrogen of the three grass types, yet produced NO_X emissions at the highest rate.

Sample	NO_X (lbs./MMBtu)
Control (100% Wood)	0.18
S1 (100% Switchgrass)	0.30
R1 (100% Reed Canarygrass)	0.66
M1 (100% Mulch Hay)	0.39

On average the 100% grass fuel samples contained more than 20 times more nitrogen than the control 100% wood pellet samples, yet the grasses only produced slightly higher levels of NO_X when burned. It is likely that these results are due to combustion temperature variables during testing. Combustion temperature plays a large part in No_X formation: more NO_X is produced at higher temperatures than at lower temperatures.

Generally, the two best methods for controlling NO_X emissions are to minimize nitrogen content in the fuel combusted and to slightly lower the firebox temperature. The standard formation of NO_X depends on the firebox temperature—the higher the firebox temperature, the more the NO_X emitted. If firebox temperatures are lowered too far, however, combustion efficiency will be adversely impacted. A balance must be achieved in system tuning: maintaining a proper temperature for total combustion of the fuel but not at such so high as to produce an excess of harmful chemicals. Efforts to control NO_X that require reduced excess air levels can result in an oxygen deficient flame and increased levels of carbon monoxide or unburned hydrocarbons.



While there are no cost-effective back-end control technologies for NO_X for systems smaller than 15 MMBtu/hour, there are such control technologies for larger systems.

While there are no cost-effective back-end control technologies for NO_X for systems smaller than 15 MMBtu/hour, there are such control technologies for larger systems. Selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) are two technologies proven at the industrial boiler scale for controlling NO_X emissions. Larger systems with higher capital costs can more readily absorb the additional costs of NO_X control technology.

At this time in Vermont, there are no NO_X emission limits for solid-fuel boiler systems below 100 MMBtu/hour, so slight increases in NO_X emissions from grasses would not likely trigger further air emissions permitting or require using more sophisticated control devices such as SCR systems for a large majority of the market.

OPERATIONAL COMBUSTION TRIALS

From April 19th to April 21st, follow-up combustion trials were conducted to test the grass pellet fuel under conditions more typical of normal boiler operations. All the pellet fuel blends tested were combusted in three-hour sessions. Each of the test burns were conducted under typical, more moderate load conditions where the combustion unit controls require the system to cycle between high-fire and low-fire settings in response to changes in demand for heat in a building. All combustion system performance measurements were recorded separately for the periods when the system was burning in high-fire conditions and periods when the systems idled down during low-fire.

Biomass Commodities Corporation supervised the test burns and recorded data and observations on the 100% grass pellets, 25% grass pellets, and 12% grass pellets at both high- and low-fire. Data was recorded hourly. There was not time to test the 6% grass pellet fuels under these conditions due to the arrival of warm weather.

The parameters measured in this series of tests were: temperature in the main combustion chamber, temperature in the exhaust stack, oxygen levels in the combustion chamber, CO and CO_2 in the exhaust gas, and excess air in the combustion chamber. Overall combustion efficiency was also calculated.

From left, clockwise: The combustion chamber of the 500,000 Btu/hour Solagen pellet boiler at All Souls Interfaith Gathering; manual feeding of the test-fuel hopper with 40-pound bags; monitoring of the combustion conditions by Gammie Air to ensure proper timing of stack gas sampling.

RESULTS

The following table shows the results of the Solagen system under **high-fire** settings for the various test pellets blends:

Sample Under High-Fire Settings	Firebox Temp. (°F)	Stack Temp. (°F)	Oxygen (%)	Carbon Monoxide (ppm)	Carbon Dioxide (%)	Combustion Efficiency (%)	Excess Air (%)
Control (100% Wood)	1,238	498	6.84	27	13.47	80.78	48.52
S1 (100% Switchgrass)	1,343	471	7.50	63	12.84	80.96	65.06
S2 (25% Switchgrass)	1,400	525	5.86	34	14.40	80.82	38.46
S3 (12% Switchgrass)	1,436	483	6.13	41	14.15	82.03	41.20
R1 (100% Reed Canarygrass)	1,299	455	7.80	4	12.55	81.26	58.68
R2 (25% Reed Canarygrass)	1,423	474	6.52	42	13.77	81.84	46.28
R3 (12% Reed Canarygrass)	1,366	508	6.60	17	13.70	81.32	45.56
M1 (100% Mulch Hay)	1,304	455	8.16	27	12.21	81.20	64.76
M2 (25% Mulch Hay)	1,400	473	5.66	125	14.41	82.30	38.56
M3 (12% Mulch Hay)	1,495	483	4.13	40	16.06	82.75	24.18

The following table shows the results of the Solagen system under **low-fire** settings for the various test pellets blends:

Sample Under Low-Fire Settings	Firebox Temp. (°F)	Stack Temp. (°F)	Oxygen (%)	Carbon Monoxide (ppm)	Carbon Dioxide (%)	Combustion Efficiency (%)	Excess Air (%)
Control (100% Wood)	296	159	19.24	629	1.63	73.56	1,070.26
S1 (100% Switchgrass)	345	211	18.92	273	1.94	66.80	892.42
S2 (25% Switchgrass)	424	222	17.96	194	2.86	73.22	653.74
S3 (12% Switchgrass)	417	228	18.32	388	2.51	72.96	672.68
R1 (100% Reed Canarygrass)	425	205	18.92	259	1.94	69.80	899.36
R2 (25% Reed Canarygrass)	471	242	17.96	194	2.86	72.52	598.12
R3 (12% Reed Canarygrass)	430	234	17.90	430	3.10	76.24	536.96
M1 (100% Mulch Hay)	482	216	18.02	564	2.80	74.62	625.64
M2 (25% Mulch Hay)	402	222	18.40	652	2.43	71.80	701.04
M3 (12% Mulch Hay)	450	239	17.90	748	2.91	73.96	567.32

Note: The results listed above vary due to differences in the fuels but also the differing load conditions for each test burn. It is impossible to exactly replicate the same combustion conditions for each test burn.

OPERATIONAL COMBUSTION TRIALS *(cont'd)*

DISCUSSION OF THE OPERATIONAL COMBUSTION TRIALS

As expected, during the operational test burns, CO levels during high-fire conditions were much lower than the levels recorded during low-fire conditions. The CO levels measured during the stack emissions testing, however, were even lower.

The extreme levels of excess air recorded during the low-fire combustion conditions were due to the system control settings not being adjusted between high-fire and low-fire cycling and the same amount of air was fed to the combustion chamber during high-fire period as was provided during low-fire. The extremely high levels of CO and lower efficiency indicate incomplete combustion and possibly higher levels of stack emissions during those periods. This illustrates the overall difficulty in constantly recalibrating the system controls to optimize the system performance given the different fuels being burned.

The Solagen pellet boiler (with auto de-ash auger in the foreground).

Wood Pellet Control

The Solagen boiler used for these grass pellet combustion trials has been successfully burning 100% wood pellets for over two years, so the 100% wood control pellet did not provide any surprises in how the system performed or the amount or type of ash produced during the test.

The boiler was set up to run at peak performance with adjustments to the air flow across the fuel and feed rate. There were no substantial clinkers or ash build-up and it can be assumed ash raking would be required every three-to-five days (as is the operational norm for this boiler using wood pellets).

Switchgrass Pellet Blends

For this test burn, the 100% switchgrass sample took longer to ignite, but once it was ignited, it burned on par with the wood pellets. BCC also observed that the switchgrass ash had very different characteristics than those of wood. The 100% switchgrass pellet caused some of the fastest forming and largest quantities of clinker ash build-up. The ash was almost glass-like; hard and brittle. The S2 and S3 pellet test fuel produced less ash of this type, as the wood content in the pellets increased.

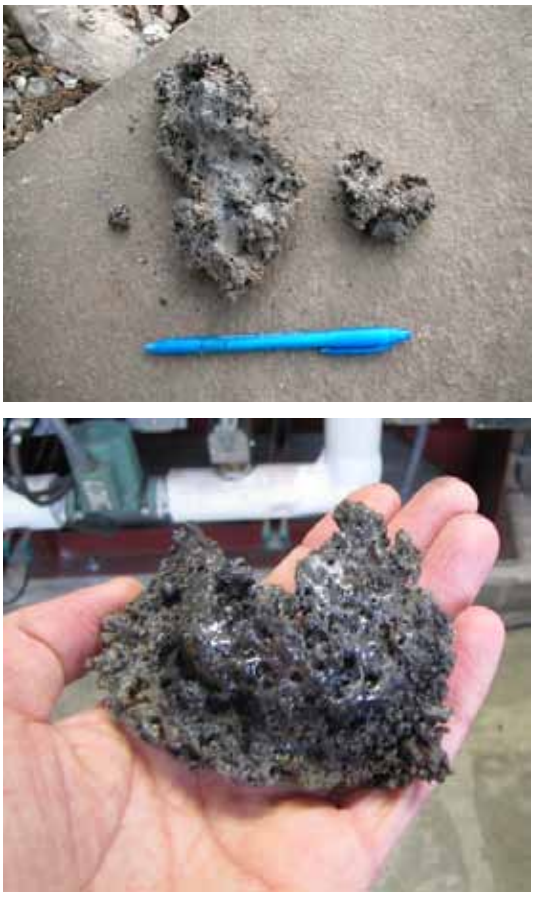
The testing was performed for three hours and over this time the fused ash was significant enough to restrict the incoming air to the burner box. Although the ash during the test was easily removed as it piled up, raking would likely increase to one to two times per day (especially for the S1 sample).

Reed Canarygrass Pellet Blends

Burning the 100% reed canarygrass produced the quickest build-up and the greatest quantity of ash among the three types of 100% grass pellets. Due in part to the ash retaining the shape of the pellet, the ash did not blow out of the burner as the wood and switchgrass tended to do. BCC increased the airflow in hopes that this would enable the ash to move out of the burner box, but the pellet shaped ash still required raking after the 3-hour test burn. BCC concluded that for the R1, R2 and R3 pellet samples, burner raking might have to occur one-to-two times per day.

Mulch Hay Pellet Blends

The mulch hay pellets (in all concentrations) encountered the most difficulties in this series of tests; from tuning the Solagen for the most optimal burn, to an excess of clinkers and fused ash during combustion. Airflow in the firebox was restricted due to the large chunks of soft, melted ash. BCC noted that some of the ash had an almost sticky texture and did not experience an easy test with this fuel, even as the wood content increased. With the M1, M2, and M3 pellet samples, the burner raking would most likely need to occur two-to-three times per day to try to maintain an efficient system.



Typical ash "clinkers" formed during the combustion of 100% switchgrass pellets.

CONCLUSIONS

A mature stand of switchgrass is expected to yield from 2-3.5 dry tons per acre in the Northeast; however, switchgrass can be a challenge to establish.

The performance testing work conducted by VGEP on grass pellet fuel production and combustion has presented a wealth of information that has helped to better understand the potential for and the challenges facing grass energy in Vermont (see summary table on opposite page).

GROWTH AND HARVESTING

A mature stand of **switchgrass** is expected to yield from 2-3.5 dry tons per acre in the Northeast, however, switchgrass can be a challenge to establish. The seed has an innate dormancy mechanism that can vary from one seed source to another. The seed from which the test grass pellets were made had a dormancy rate of about 80%, which means many of these seeds do eventually germinate, but over a very long period of time (a few months to even a year) allowing weeds to initially outcompete the switchgrass.

At the Borderview farm, which supplied the switchgrass for these trials, by the second year, the rows started to fill in with switchgrass. The whole stand was burned in April 2008 to destroy old weed residue. It was also sprayed with herbicide to keep the quackgrass from becoming a problem.

The field was harvested for hay that year in October 2008 but was fairly weedy. It was not until the third year that the stand was thick enough and mature enough to provide a good harvest of relatively pure switchgrass; however, an herbicide application was needed that year to keep it “clean.”

Being a warm season grass, it doesn't start regrowing until May. By that time, many cool season perennial grasses such as reed canarygrass, quackgrass, or timothy as well as broadleaf perennial weeds such as milkweed will have started growing and provide early competition. The evidence suggests that once the switchgrass stand is thick and mature, it will better compete with these species but this can take three or four years. The advantage, however, of a warm season grass like switchgrass is that it does not reach reproductive maturity until late in the season and, with a few frosts in early fall, the tops will die and begin drying out. This makes it very conducive for a mid- to late-fall harvest.

Reed canarygrass yields up to 3 tons per acre in the Northeast and is much easier to establish even though it, too, can sometimes have seed quality issues. A spring seeding of reed canarygrass, however, can produce a reasonable quantity of biomass in the first year (about half of full potential) and have a full stand by the next year. Being a fast growing, cool season grass, it initiates growth in early spring and competes well with other perennial species; therefore, very little or no herbicide is required to maintain a stand. It has an appetite for nitrogen fertilizer, however, which is needed to promote tillering and yield.

A major challenge with reed canarygrass is the high ash content and harvest management. Normally, reed canarygrass has reached full reproductive maturity by mid July. So late July would be an optimum time to harvest. This is not compatible, however, with known harvest strategies to reduce ash; for example, leaving the cut grass in windrows in the field for two weeks. With a late July harvest, new leaf growth from the crown begins emerging up through the windrows making it difficult to harvest the hay. Waiting to harvest till later in September has been shown to create other problems; the seedheads will have lodged and new leaf growth initiates result-

Pellet Sample	Energy Content	Ash Content	Chlorine	Emissions	Overall Performance
Control (100% Wood)	Good	Super Premium	Acceptable	Meets all regulations at current time for this size boiler	Normal
S1 (100% Switchgrass)	Good	Utility Grade	Close to Limit	Meets all regulations at current time for this size boiler	Significant clinker formation
S2 (25% Switchgrass)	Good	Standard Grade	Acceptable	Meets all regulations at current time for this size boiler	Some clinker formation
S3 (12% Switchgrass)	Good	Premium Grade	Acceptable	Meets all regulations at current time for this size boiler	Minimal clinker formation
S4 (6% Switchgrass)	Good	Premium Grade	Acceptable	Meets all regulations at current time for this size boiler	Untested
R1 (100% Reed Canarygrass)	Insuffi-cient	Unacceptable	Unacceptable	Meets all regulations at current time for this size boiler	Minimal clinker formation
R2 (25% Reed Canarygrass)	Adequate	Standard Grade	Acceptable	Meets all regulations at current time for this size boiler	Minimal clinker formation
R3 (12% Reed Canarygrass)	Good	Premium Grade	Acceptable	Meets all regulations at current time for this size boiler	Minimal clinker formation
R4 (6% Reed Canarygrass)	Good	Premium Grade	Acceptable	Meets all regulations at current time for this size boiler	Untested
M1 (100% Mulch Hay)	Adequate	Utility Grade	Unacceptable	Meets all regulations at current time for this size boiler	Significant clinker formation
M2 (25% Mulch Hay)	Adequate	Standard Grade	Unacceptable	Meets all regulations at current time for this size boiler	Some clinker formation
M3 (12% Mulch Hay)	Good	Premium Grade	Acceptable	Meets all regulations at current time for this size boiler	Minimal clinker formation
M4 (6% Mulch Hay)	Good	Premium Grade	Acceptable	Meets all regulations at current time for this size boiler	Untested

CONCLUSIONS *(cont'd)*

Fall harvest of reed canarygrass at the Borderview Farm in November 2009.

ing in even higher ash content. A preferred strategy that needs some testing might be to harvest reed canarygrass in mid-to-late July, but leave the windrows in the field for only one week (instead of two or three) before new growth emerges from the crown. If the stand is mowed just before a predicted rainfall, this could further facilitate the leaching of minerals and in turn, lower the ash content in the pelletized fuel.

All the source grass used in the making of the test pellets came from fields overseen by UVM Extension researchers. Using grasses from known sites where soil type, crop rotation, and fertilization history is known is extremely valuable for such a study.

Although 40-pound square bales were chosen for use in this study, due to the comparatively easier manual handling and processing (chopping and grinding) in smaller test volumes, round bales could be used for larger volume production of pellets.

MATERIAL PROCESSING AND PELLETIZATION

While chopping and grinding grass fibers are difficult in the relatively small volumes needed for this study, systems to reduce the particle size can and have been effectively engineered for larger production volumes. For the purposes of this study and if similar volumes of grass/wood pellets were needed for future tests, grasses can be chopped and reground using similar mobile equipment, but further rudimentary engineering should be conducted in effort to solve the collection and storage of the chopped grass pneumatically discharged by the bale chopper/mulcher. A simple solution would be to design and fabricate a fine wire mesh open-bottomed box situated above a large storage container. Discharging the chopped grass fiber into this box would allow grass to drop into the storage container below but allow the high velocity air to escape through the wire mesh without constantly blowing directly into the storage container with no air outlet.

Producing 100% grass pellets at this scale proved to be challenging. Grass fiber alone does not flow very well and tends to bridge and ball up very easily. The pellets formed with 100% grass were not as durable or well formed as the wood/grass blend pellets. This can be attributed to the low levels of lignin in the material as well as the higher moisture content of the grass fibers. A binder such as cornstarch is required to produce a good quality pellet with sufficient density and durability. Blending wood with the grass fiber helps the durability issue considerably. Another issue that surfaced during pellet production was that the low bulk density of grass took up a lot of volume in the mill for its overall weight—thereby reducing the rate of production. It is unclear how this issue could be resolved.

GRASS PELLET FUEL PROPERTIES

Results from the laboratory analysis of the various grass pellet fuels were by and large as expected, however, some of the test burns did not conform to anticipated results (based on the lab analysis). Pellets with increased percentages of grass fibers contained dramatically higher concentrations of ash, nitrogen, sulfur, and chlorine than the control sample of 100% wood, as predicted. Of the three grasses, the lab analysis from reed canarygrass had the highest ash content, but instead of producing the largest quantity of ash and clinkers, relatively small amounts of clinkers formed during the test burns. Conversely, switchgrass had the lowest ash content of the three grass types and yet produced a considerable amount of fused ash clinkers. Mulch hay pellets contained less ash than reed canarygrass but still produced considerable ash and clinkers during combustion trials. In many cases it is not the amount of total ash in the fuel that results in the formation of clinkers—it is the specific mineral make up of the ash. Further analysis should be conducted to examine the alkali mineral content of both the switchgrass pellets and the reed canarygrass pellets. It is quite likely that while the switchgrass had lower levels of total ash content, it had higher levels of clinker forming alkali minerals.

STACK EMISSIONS

The stack emissions testing conducted by Gammie Air showed that the grasses with higher ash content such as the mulch hay and reed canarygrass produce much more particulate matter from their combustion. Lower ash content grasses like switchgrass, especially blended with wood fiber would likely produce PM emissions comparable to 100% wood pellets. Stack emissions data for NO_X showed higher levels from grasses than the control wood fuel. Existing air quality regulations in Vermont exempt boilers smaller than 3MMBtu/hour output capacity from specific emission thresholds for both PM and NO_X. However, boilers larger than 3MMBtu/hour output capacity are subjected to specific limits and require Best Available Control Technology to limit emissions of PM and, at very larger scales, NOX. The new draft EPA boiler emissions rules call for significantly lower PM emissions limit (less than 0.03 pounds/MMBtu) for all boiler sizes (new and existing) and require all existing boilers to have biannual system tune-ups to achieve target CO levels. It is not clear at this time whether the proposed draft rules will be adopted as is, or whether significant changes to the rules will be made.

Pellets with increased percentages of grass fibers contained dramatically higher concentrations of ash, nitrogen, sulfur, and chlorine than the control sample of 100% wood, as predicted.

CONCLUSIONS *(cont'd)*

Today, there are numerous companies who claim to have equipment that is able to "burn anything" but there are few who have demonstrated their equipment will perform reliably using grass fuels.

COMBUSTION SYSTEMS AND PERFORMANCE

The operational combustion trials demonstrated that clinkering issues were most common in the switchgrass and mulch pellets across all grades. The 100% grass pellets produced the most rapid and highest volume of clinker build-up. Testing on a moving grate burner (automatically conveys fuel as it is combusted and deposits ash into ash removal system, and in the process make it harder for clinkers to bond to the combustion grate) as a next step might help relieve this issue as the boiler system used had a stationary or fixed combustion grate.

When burning grass fuel containing higher levels of chlorine and alkalis, in oxygen-rich combustion conditions, the by-product gases will be corrosive to the metal lining of the heat exchange surface area and exhaust gas duct work. In the absence of chlorine, or alkali chlorides, boiler tubes form a thin oxide layer that resists subsequent oxidation and corrosion; in this case, oxygen cannot penetrate through the oxide layer to the metal below. Chlorine gases, however, can penetrate the oxide layer, enabling corrosion. Possible solutions to this corrosion problem are:

- Blending grasses with other fibers such as wood to lower chlorine and alkali levels.
- Replacing boiler tubes using more corrosion resistant materials like stainless steel.
- Thicker boiler tube walls.
- Maintaining sufficient and proper air distribution to secondary and tertiary combustion phases.
- Avoiding excessive oxygen in furnace.

These possible solutions should be tested to see what presents the best reduction for corrosion in existing boiler designs.

Testing done by BCC demonstrated that ash management is the highest operational priority to consider when using grass as boiler fuel. With this type of burner system (with no automated ash removal), the most useful information gathered was an estimation of how many times the burner box would have to be raked and cleaned to keep the system running in a given period of time. If test burn durations were extended to 24-hour or even 48-hour periods, there would be a greater understanding of the true labor and system maintenance needs. Future efforts to test grass pellet combustion should conduct longer test burns, and use larger boilers (preferably with traveling grates and with automatic ash disposal capacity).

SUMMARY

In Vermont, hay crops and dedicated energy grasses can be successfully grown and harvested using conventional methods and existing farm equipment. Hay and energy grass can be successfully pelletized into various densified fuel form factors (briquettes, large diameter "pucks" or tablets, as well as small diameter pellets). These materials can be blended at varying concentrations with readily available wood fibers to increase overall pellet fuel quality.

Pure grass pellets should not be sold for use in residential pellet stove heating appliances designed to burn wood because of the high ash content of grass pellets and their corrosive flue gas. There is potential, however, for their use in larger boilers and heating systems that have been engineered to meet these challenges using adjustable feed rates, traveling grates to break up clinkers, the appropriate air and emission controls, and corrosion resistant materials such as stainless steel. Other potential end uses would be in smaller appliances that have been specifically engineered to meet the challenge of high ash grass pellet fuel.

Today, there are numerous companies who claim to have equipment that is able to "burn anything" but there are few who have demonstrated their equipment will perform reliably using grass fuels. Therefore, VGEP is continuing the examination of new and existing heating appliances (furnaces and boilers) that claim the ability to reliably burn high ash fuels such as grass pellets. This research is needed in order to identify the most suitable heating appliances for this fuel. From the results of the laboratory analysis conducted by Twin Ports Testing, Inc. and the emissions testing done by Gammie Air Test Monitoring, switchgrass, as a species, most closely mirrors the baseline performance of wood pellets and out-performed reed canarygrass and mulch hay. Despite the clear superiority of switchgrass, blending with wood fiber is still essential if the product will be combusted in systems designed to burn low ash fuel like wood.

VGEP has identified two principal strategies for expanding grass fiber use as a heating fuel in Vermont:

1. Blend grass with wood pellets to meet existing industry norms for fuel and appliances.
2. Build a new market for 100% grass fuel by identifying or developing the appliances capable of burning grass fuels. Additionally, minor adaptation of wood pellet manufacturing equipment and processes may be necessary to better suit the material handling characteristics of grass fiber.

Vermont is experiencing slow and steady growth of pellet deliveries in bulk to smaller commercial and institutional heating customers. The first option could provide fuel to meet this growing demand by blending grass and wood fibers (i.e., 10-20% grass and 80-90% wood) to produce a PFI standard-grade fuel pellet for use in boilers in the 250,000-1.5MMBtu range. Heating systems of this size (and up) are typically slightly more tolerant as far as pellet fuel quality is concerned, opening the way to utilize grass and wood blended fuels.

To fully assess the potential of this market, further economic feasibility work should be conducted to determine the production costs of pellets made with grass and wood blends and to gauge the interest of the pellet consuming market for this type of product.

The second strategy (developing a new market capable of burning 100% grass pellets) also warrants further examination. Despite the prevalence of wood pellet and woodchip-fueled heating in Vermont, there may be a niche market opportunity for 100% grass fuels. For instance, replacing fossil fuels with grass pellets on Vermont farms is a logical opportunity, as farms can produce and possibly utilize the grass fuel to replace their No. 2 oil and propane for heating buildings and greenhouses. An economic assessment needs to be conducted to determine the production costs of farm-scale grass pelletization and the potential fuel savings of grass pellets over other heating fuels. Other market development scenarios using 100% grass pellets could emerge that will need further in-depth analysis as well.

As a result of this study and supporting research by others, VGEP maintains that it is in the interest of both the pellet fuel consumer and the pellet fuel manufacturing industry, that customers know fully the quality and performance differences between grass and wood pellets. Grass pellet marketers must therefore communicate effectively as to the likely operational challenges of using grass fuels.

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NEXT STEPS

The next steps in determining the feasibility of grass energy in Vermont should include a robust economic assessment of the costs of manufacturing grass pellets under different scenarios.

The next steps in determining the feasibility of grass energy in Vermont should include a robust economic assessment of the costs of manufacturing grass pellets under different scenarios. For instance, what changes can be anticipated at a centralized (stationary) pellet mill compared to utilizing mobile equipment (at different scales) to process the grass "on location"?

As part of this economic assessment, key variables such as the cost of energy (fuel, electricity, diesel, biodiesel, etc.), subsidies paid to farmers (e.g., USDA's Biomass Crop Assistance Program), and economies of scale in production costs, must all be considered. Once the grass pellet production costs are fully understood, target wholesale and retail price points can be projected and compared against other heating fuels, including liquid fossil fuels and wood fuels.

VGEP acknowledges the growing body of knowledge that is accumulating through grass energy research and development efforts in the Northeast, and elsewhere in the United States and internationally. It is also important to recognize that the process of utilizing grass as a heating fuel in modern combustion systems is in its infancy. As a result, there are, as of today, very few examples of enterprises that have been launched and sustained, that rely on grass energy as a principal source of revenue.

VGEP will continue to work with those involved in grass-to-fuel research, development, and production; supporting efforts to economically and sustainably replace a portion of the region's fossil fuel use in ways that maintain a healthy environment while strengthening the local economy.

FOOTNOTES

[1] Source: The 2007 USDA Census of Agriculture, National Agricultural Statistics Service (NASS)

[2] It should be noted that the boiler chosen for these test burns was designed to burn low-ash content wood pellets.

[3] For full details of the "real world" combustion testing see Appendix C – BCC Report.

[4] As with any process, there is potential for error in mixing and getting the exact percentages in each and every pellet.

[5] http://www.pelletheat.org/3/industry/index.html.

[6] PFI standards are for Chloride whereas laboratory analysis presented later in this report is for Chlorine. In this study chlorine and chloride are used interchangeably.

[7] Proximate and Ultimate analyses are common tests used for determining the properties of solid fuels including biomass materials. Proximate analysis gives the fixed carbon, volatile and ash content of biomass, helping to understand how fuels will combust. The ultimate analysis gives the elemental (C, H, O, S, N) composition of the fuel.

[8] C. Ryu, et al. Effect of Fuel Properties on Biomass Combustion, Nov. 2005.

[9] Dr. Jerry Cherney, Cornell University – www.grassbioenergy.org.

[10] PPM or parts per million is the same as ug/g (micrograms per gram).

[11] For further information on US EPA stack testing methodology go to – http://www.epa.gov/ttnemc01/promgate.html.

[12] For further information on the new draft boiler rules from the EPA go to - http://www.epa.gov/ttn/atw/boiler/boilerpg.html.

[13] Hinckley J. and Doshi, K. Emission Controls for Small Wood-Fired Boilers. May 2010.

[14] PM control technologies include single cyclones, multi-cyclones, baghouses, and electrostatic precipitators.

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