PRODUCING SOLID FUEL FROM NON-RECYCLABLE AGRICULTURAL PLASTICS

M. J. Lawrence, J. W. Garthe, D. R. Buckmaster

ABSTRACT. A plastic-derived fuel production process was developed and has been shown to be effective for non-recyclable plastics that are widely used in agriculture and normally discarded. A machine was designed, constructed, and evaluated with regard to energy balance and fuel nugget production. The hydraulically driven machine processed dirty, non-recyclable plastics by first compacting and then extruding them through four internal channels of a heated die. The process produced plastic fuel nuggets with a thin, melted exterior which trapped unmelted plastic in the interior. The Plastofuel™ nuggets were 3.8 cm (1.5 in.) wide, 3.8 cm (1.5 in.) high, and were cut to a length of 5.1 cm (2 in.). All aspects of machine operation, with the exception of feedstock loading, were automated and controlled by an onboard microprocessor. The machine was equipped with two data loggers to collect hydraulic and electric system energy metrics. Component positions, electric power consumption, and hydraulic system pressure were recorded and converted to total energy consumption for all production runs.

Energy content of the Plastofuel™ formed using clean household plastic and unused mulch film was 45.5 MJ/kg (19500 Btu/lb). Plastofuel™, formed with dirty, used mulch film and used plastic pots and trays, had an energy content of 38.8 MJ/kg (16700 Btu/lb). A system energy ratio was determined by dividing the combined hydraulic and electric energy used for Plastofuel™ formation into the potential energy stored in all plastic nuggets formed for a single test run. The highest energy ratio (Eout/Ein) from all test runs was 47. The maximum Plastofuel™ production rate achieved with the machine was 27.6 kg/h (61 lb/h).


The use of plastics in agriculture has increased dramatically since their introduction to the industry in the 1950s. Termed plasticulture, this practice is widespread and used for such on-farm applications as round bale covers, nursery trays and pots, mulch films, drip irrigation tape, trench silo and greenhouse covers, and chemical containers. Due to their contaminated condition, most agricultural plastics are used only once and then discarded rather than reused or recycled. Piles of used plastic products on farms are an eyesore and environmental hazard. Nearly all plastic materials in use today are petroleum-based products with a high heating value. If these waste plastics could be transformed to solid fuel nuggets and co-fired with coal in coal-fired boilers or burned in a specially designed high-temperature furnace, this alternative energy source would alleviate the burden of disposal and might also provide an additional revenue stream to farmers.

The ultimate research goal for this work was the design, construction, and analysis of an automated Plastofuel™ production system using a linear knife grid concept. The previous Plastofuel™ processing design used a hydraulic cylinder to push shredded plastic through a single cylindrical die. This prototype was labor intensive and was not outfitted with instrumentation to log energy usage data. The new research was intended to log machine production rate and energy usage data. With this new machine, capacity was increased by increasing the die size to incorporate shear knives upstream of four parallel die channels. The machine was equipped with electronics to capture machine performance statistics and determine the ratio of potential energy stored in the Plastofuel™ nuggets to the hydraulic and electric energy used in their formation. Design considerations began with a review of current literature pertaining to waste agricultural plastic availability, current disposal methods, and plastic physical properties.

PLASTIC USE IN AGRICULTURE

Many different types of plastic can be found in use for nearly every crop and at nearly every stage of production in modern agriculture. Grain, forage, and horticultural crops benefit from plastic utilization. For example, plastics in grain and forage crops are used for fertilizer and herbicide storage, silage bale wrapping, and trench silo coverings. Horticultural farmers use plastic nursery trays and pots, drip irrigation...
tubing, mulch film, row covers, and high tunnel and greenhouse coverings.

Two general categories of agricultural plastics are films and containers. The obvious difference is rigidity. Plastic film products are less rigid than plastic container products. Agricultural films are primarily low density polyethylene (LDPE) but can also be polypropylene (PP). Agricultural containers are primarily high density polyethylene (HDPE) but can also be polystyrene (PS) or PP.

At the current annual consumption rate of 2.25(10^6) Mg [4.96(10^9) lb], the amount of plastic used in agriculture worldwide is staggering (Hussain and Hamid, 2003). The only published comprehensive study of plastic use in American agriculture was completed by Amidon Recycling at the request of the American Plastics Council (APC) (APC, 1994). The 1994 study not only categorized and quantified the plastic use annually in the U.S. agricultural sector, but also indicated the type of plastic used in each application. A summary of these findings is shown in figure 1.

Since this study was completed in 1994, subsequent studies have shown that the amount of plastics used in U.S. agriculture increased to 3.86(10^5) Mg [8.5(10^8) lb] in 1998 and 4.54(10^5) Mg [1(10^9) lb] in 2001 (A. Amidon, personal communication, 12 August 2005).

**PLASTIC DISPOSAL**

Of the more than 2.35(10^5) Mg [5.19(10^8) lb] of plastic used, it was estimated that less than 5% were recycled and less than 5% were incinerated for energy recovery (APC, 1994). That left approximately 2.11(10^5) Mg [4.66(10^8) lb] of plastic disposed of through less desirable methods. Currently, there are three primary methods to handle waste agricultural plastic: recycling, incineration (mostly through open burning), or burying in a landfill site (Garthe, 2004; Warner, 2005).

The disposal of post-consumer, non-agricultural plastics in the United States is more completely documented. Post-consumer plastics, those that have served their intended purpose, make up roughly 9.4% of municipal solid waste (MSW) by weight before recycling. Of this percentage, 3.8% is recycled. Remarkably, the remaining 5.6% of MSW plastics by weight destined for the landfill make up an estimated 16% to 25.1% of the total waste by volume (Harper, 2002; Rathje and Murphy, 1992). Although this research focuses on the recovery of waste plastics from the agricultural sector, the potential for plastic recovery from the MSW stream should not be overlooked.

Plastofuel™, the plastic-derived fuel nuggets that are the focus of this research, is considered the last stop for a waste product, because it will be incinerated solely for energy recovery. Plastofuel™ creation should only be considered when product reuse or recycling is not an option.

**PLASTIC ENERGY VALUES**

Currently, fossil fuels are the primary source for producing U.S. electrical energy, as they account for 71% of the total production (USDOE, 2003). The relatively high energy content of fossil fuels makes them the most important single resource for energy production. The fossil fuels, petroleum and natural gas, are the primary feedstock for plastics (Muccio, 1994), so plastics also carry a high energy content. Table 1 provides heating values for plastics and other common materials.

**OBJECTIVES**

The goal of the research was to improve existing Plastofuel™ production method. The objectives in support of the goal were to:

- Design and fabricate a system to form plastic derived fuel nuggets from waste agricultural plastics using a linear knife concept.
- Determine maximum plastic fuel nugget production rate, then optimize the energy input settings to produce plastic fuel nuggets using an electro-hydraulic circuit and feedback mechanisms.

<table>
<thead>
<tr>
<th>Material</th>
<th>Heating Value (MJ/kg, Btu/lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel oil</td>
<td>48.6 (20,900)</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>46.3 (19,900)</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>44.1 (19,000)</td>
</tr>
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<td>Polystyrene</td>
<td>41.4 (17,800)</td>
</tr>
<tr>
<td>Tires</td>
<td>30.1 (13,000)</td>
</tr>
<tr>
<td>Subbituminous coal</td>
<td>27.3 (11,700)</td>
</tr>
<tr>
<td>Wood (pine)</td>
<td>22.3 (9,600)</td>
</tr>
<tr>
<td>Wood (oak)</td>
<td>19.3 (8,300)</td>
</tr>
<tr>
<td>Municipal solid waste (dry)</td>
<td>16.2 (7,000)</td>
</tr>
<tr>
<td>Municipal solid waste (50% moisture)</td>
<td>7.9 (3,400)</td>
</tr>
</tbody>
</table>
Determine the energy efficiency of the system by comparing energy used to form plastic fuel pellets and the potential energy stored in the nuggets.

**METHODS AND MATERIALS**

**MAJOR MACHINE COMPONENTS AND OPERATION**

Figure 3 shows the control side of the machine. Each major component is listed below with a brief description and a label corresponding to its location in figure 3.

A. The machine was initially loaded with non-recyclable, plastic feedstock through the feed chute.

B. The compaction chamber housed a hydraulic cylinder linked to a compaction plunger, both in a vertical orientation. The plunger reduced the size of large items loaded into the machine by shearing and compacting the plastic feedstock.

C. The extrusion chamber housed a hydraulic cylinder linked to an extrusion plunger, both in a horizontal orientation. The plunger sheared the compacted feedstock and then forced the plastic into the linear knife grid.

D. The die assembly was heated using 16 electric heating strips mounted to the exterior surface. At the die assembly entrance, the plastic was forced through a linear knife grid and into four parallel channels. The exterior of the plastic was melted as it passed through the die assembly. The die assembly was insulated from the frame using fiberglass board to reduce heat loss due to conduction.

E. As the plastic exited the die, each nugget was cut to length using vertically oriented hydraulic cylinders, one for each die channel. There was a whisker activated limit switch mounted 5.1 cm (2 in.) beyond the die opening, and as the extrudate emerged and touched a limit switch, the corresponding cut-off cylinder was actuated.

F. Each of the six hydraulic cylinders was controlled by its own directional control valve located on a valve manifold. Quick couplings were located here to connect the machine to a hydraulic power unit.

G. The machine electronics and wiring were centrally located in a control box, which housed the machine logic microprocessors, fuses, terminal strips, two data loggers, and several solid-state electrical relays.

**HYDRAULIC SYSTEM DESIGN**

The hydraulic system used a load-sensing pump because this machine had widely varying flow and pressure requirements. For this design, load-sensing hydraulic circuits maximized system efficiency by providing only the flow and pressure required by the circuit components (Cundiff, 2002). With a research goal to maximize the machine energy balance, minimizing hydraulic power was critical. As detailed in figure 4, the hydraulic schematic was designed such that the maximum system pressure required by any of the six hydraulic cylinders was transmitted to the pump via a load-sense line.

The compaction and extrusion cylinders were electronically controlled and capable of stopping mid-stroke, so three-position, spring-centered, closed-center, double-solenoid valves were selected. The speed of the compaction and extrusion cylinders could be manually adjusted by sandwich-style flow controls mounted between the valve and the valve manifold. The cutting cylinders were also electronically controlled but only required to fully extend and fully retract; for this reason, two position, spring return, single solenoid valves were selected. Valves were made by NACHI (Macomb, Mich.) and conformed to the industry standard, D03 mounting style. All valves were mounted on an aluminum manifold.

The hydraulic system was outfitted with a hydraulic pressure transducer. The pressure transducer (Model PX603) was manufactured by Omega Engineering (Stamford, Conn.) and threaded directly into a gauge port on the hydraulic manifold. The transducer had a best fit straight line accuracy specification of ±0.4%. The transducer was powered with 12VDC and provided a 1-5V output signal which corresponded to hydraulic pressures from 0-34 MPa (0-5000 psi). This output was directly connected to the control system as a system input.

**CONTROL SYSTEM DESIGN**

The Plastofuel™ machine control system monitored all hydraulic and electric system input signals and provided
system output signals based on a control algorithm. The system was a Parker Hannifin (Cleveland, Ohio) IQAN® controller area network (CAN) (Parker Hannifin, 2003); a CAN system uses a modular approach to collect inputs and provide outputs using a master module and a single serial communication line between components. For this research, an XP expansion module and an XS expansion module were used with a Master Display Module (MDM), which was displayed on the panel of the control box. The MDM was capable of displaying any system variable, but was set to automatically display the locations of the compaction and extrusion plungers.

The control box housed the IQAN XP and XS expansion modules, terminal strips for all AC and DC voltages, a terminal strip for IQAN inputs, several solid-state relays, and a 12VDC power supply. Two electrical supply lines entered the control box: a single phase, 220V AC line, and a 115VAC line. The 220V line was only used for the die heaters. The 115V line provided power for the electrical power consumption data logger, the temperature controllers, and an attached laptop computer which interfaced with the IQAN system to log hydraulic system data. The 115V line also connected to a 12VDC power supply to run CAN components and all sensors and switches.

The control panel also included five temperature controllers (Model CN77R343) made by Omega Engineering. Each unit controlled one heating zone on the die assembly. Each controller activated only those heaters in a single heating zone, and each zone was equipped with its own thermocouple within the die assembly housing.

**DATA COLLECTION AND ANALYSIS**

One goal of this research was to perform an energy analysis of the Plastofuel™ machine. This required documenting the energy used to form the nuggets and the energy content of the Plastofuel™ produced. Total energy consumed
by the Plastofuel™ machine included electrical energy and hydraulic energy.

**Electrical Energy Consumption**

An accurate account of the electric energy used by the machine during nugget formation required the use of a specialized data logger. The data logger that recorded machine electrical usage was an ElitePro Recording Polyphase Power Meter made by DENT Instruments (Bend, Oreg.). Jumpers were connected to both the incoming 220V and 115V lines to measure voltage readings, and current transformers were also affixed around both lines to measure current readings. These readings were communicated to a laptop running the ELOG 2002b software via a serial connection (ELOG, 2002). The software converted the voltage and current readings to average power consumption with three second intervals.

Power readings from the collected data were converted to energy consumed during each 3-s interval. These energy usage statistics were summed over the test duration for a total electrical energy consumption value.

In an effort to increase machine throughput, some feedstock was shredded before being loaded into the machine. When shredded feedstock was used, the electrical energy used to shred the feedstock was added to the total electrical energy consumption value. The waste agricultural plastics shredded for testing included 470 kg (1000 lb) of film plastics (dirty, wet LDPE mulch film and drip tape) and 520 kg (1100 lb) of rigid plastics, specifically dirty HDPE and PP buckets, pots, and trays. The shredder was powered by a 37-kW (50-hp) electric motor (S/N U3960904392) manufactured by Lincoln Electric (Grafton, Wis.). The motor had a power factor of 0.80 when drawing 45 A at 480VAC. This resulted in an average energy consumption rate of 0.08 kW·h per kg of plastic for the shredding process. The shredder was equipped with a 5-cm (2-in.) screen.

**Hydraulic Energy Consumption**

The MDM component of the CAN system was used to log hydraulic system information. The MDM could display and record up to ten system variables during operation. It recorded values of selected variables every 50 ms. The following variables, required to calculate total hydraulic power, were recorded during each test run:

- Hydraulic system pressure
- Compaction cylinder location
- Extrusion cylinder location
- Hydraulic flow
- Valve solenoid activation for cutting cylinder 1
- Valve solenoid activation for cutting cylinder 2
- Valve solenoid activation for cutting cylinder 3
- Valve solenoid activation for cutting cylinder 4
- Heaters “ready light”

Power is a function of hydraulic pressure and flow. Flow was determined by recording the location change of each cylinder over a 50-ms time step and calculating the flow required to produce that cylinder motion. Leakage internal to the hydraulic system was considered to be negligible.

The compaction and extrusion plungers were equipped with potentiometers that provided feedback regarding each plunger location throughout the cylinder stroke. The cutting cylinders, however, did not have instrumentation for position sensing. Calculating the flow to each cutting cylinder was accomplished by recording the time for cylinder actuation during both extension and retraction, and then adding this flow each time a cutting cylinder valve solenoid was energized.

Total hydraulic flow was calculated for each 50-ms time interval during the test run by determining the change in volume of the hydraulic fluid in the compaction, extrusion, and cutting cylinders. This total flow was multiplied by the hydraulic system pressure recorded during the same time interval and an instantaneous hydraulic power was calculated. The power used in each time interval was multiplied by the time interval duration resulting in energy consumed. The total energy consumption by the hydraulic system was determined by summing all energy values for each time interval in the test run.

**Plastofuel™ Energy Content Analysis**

Energy content of the Plastofuel™ nuggets was evaluated at the Penn State Combustion Laboratory. The combustion lab technician tested the nugget samples in a model 1241 adiabatic oxygen bomb calorimeter manufactured by Parr Instrument Company (Moline, Ill.).

Two types of feedstocks were tested for a high heat value – (type 1) a mixture of clean waste agricultural plastic film and clean household plastic waste, and (type 2) a mixture of dirty agricultural pots and film. A total of 10 sample nuggets were randomly selected from four different tests using the first type of feedstock. Similarly, a total of 10 sample nuggets were randomly selected from four different tests using the second type of feedstock.

Testing in the bomb calorimeter required a sample size of 1 g, yet a typical nugget weighs 60 g. A sanding disk was used to generate the powdered samples from nuggets.

Sample preparation began by cleaning the disk, tray, and clamp with denatured alcohol to remove foreign matter. Each of the ten nuggets of the same variety was then clamped below the sanding disk, and the drill press was lowered onto the nugget. The fine particles removed from the nugget were collected. The process was repeated for the second feedstock variety. A sample size of approximately 100 g was collected from each feedstock variety.

Bomb calorimetry testing was completed by a lab technician according to American Society for Testing and Materials (ASTM) method 5865-04 for coal. Four test replications were required with each feedstock type in order to satisfy a minimum variability between samples of 0.17 MJ/kg (50 Btu/lb).

**Machining Testing**

Twenty-two test runs were completed with the machine in automatic mode to determine maximum production rate. Melt depth, nugget density, and energy consumption data were also collected during these test runs. The test run durations were 20 min (9 runs) and 10 min (13 runs).

At least one production rate test run was completed for each die temperature of 125°C, 135°C, 145°C, 155°C, 165°C, 175°C, 200°C, and 220°C. Multiple test runs were completed at die temperatures of 155°C and 175°C because these temperatures appeared to produce optimal conditions.
of high throughput rates without compromising the nugget quality.

Each test began by placing ample feedstock near the machine. All five die heating zones were pre-heated to the test run temperature. After the die reached test temperature, the machine was operated in manual mode to force out the plastic which was in the die during pre-heating. Plastic that had been in the die during pre-heating, rather than machine steady-state operation, was discarded.

Just prior to machine start-up, both electrical and hydraulic data loggers were activated. After the test duration, the data loggers were disabled, and the raw data was copied to a laptop computer. The Plastofuel™ nuggets formed were collected, measured, photographed, and placed in a labeled bag. The total mass of all nuggets produced during the test run was then weighed to the nearest 1 g (0.002 lb) using a model PE6 scale manufactured by Mettler Instrument Corporation (Columbus, Ohio) which was calibrated using calibration weights prior to use.

## RESULTS AND DISCUSSION

### MAXIMUM PRODUCTION RATE

The maximum machine production rate was 27.6 kg/h (60.8 lb/h) with type 2 feedstock and a die temperature of 220°C. Over the course of the 22 production rate tests, tests run with die temperatures of either 155°C or 175°C produced the best results – high quality nuggets at reasonable rates. Production rates at these temperature settings were not different (P < 0.05).

### SYSTEM ENERGY ANALYSIS

Analysis of the system energy efficiency required a comparison of energy consumed by the machine to potential thermal energy stored in the Plastofuel™ nuggets formed. Data collected during all test runs were used for this analysis.

**Plastofuel™ Energy Content**

The Plastofuel™ energy content results are listed in table 2. Both type 1 and type 2 feedstock contained what appeared to be nearly equal proportions of HDPE, LDPE, and PS. A weighted average for a mixture of this type should have a heating value of 45.4 MJ/kg (19500 Btu/lb) using the values from table 2. Type 1 feedstock was clean plastic with insignificant contaminants present to reduce the energy content. Type 2 feedstock was used agricultural plastic with visible contaminants throughout. These contaminants reduced the energy content (table 2).

**System Energy Ratio**

The system energy ratio was determined for each test run by dividing the total energy consumption during processing feedstock into the total energy content of the Plastofuel™ nuggets formed. To compare these two values, the total energy consumption data collected during a test run by the hydraulic system and electrical system data loggers were added to the energy consumed during the shredding process, if applicable. The total energy consumed was compared to the energy content of the Plastofuel™ nuggets formed using a heating value from table 2.

The energy ratios ranged from 27 to 47 with a mean of 35 (table 3). A regression analysis of the shredded dirty feedstock (#2) data (not shown) showed that, within the ranges of tests conducted, higher die temperature (p = 0.08) and higher production rate (p = 0.03) lead to a higher energy ratio reflecting a more efficient process. With the shredded feedstock, each increase in production rate of 1 kg/h increased the energy ratio by 0.65. The maximum ratio (47) occurred with a die temperature of 155°C and clean unshredded feedstock. The second highest ratio (45) was also with clean unshredded feedstock at a slightly lower feed rate. Minimizing (or eliminating) shredding energy is key to optimizing overall efficiency, however, shredding may be necessary to achieve target production rates (as with the machine developed and tested). The considerable energy gain from this waste to energy process provides ample opportunity for material collection, storage, handling, and transportation yet still result in a positive net energy return.

## CONCLUSIONS

This research provided scientific evidence for a viable solution for the problem of non-recyclable agricultural plastics. It represents the first attempt to automate Plastofuel™ production and quantify an energy analysis for the process. After final assembly and minor machine modifications, acceptable Plastofuel™ nuggets were produced from waste agricultural plastics using a unique and completely automated machine. The final system had components to reduce the size of and compact non-recyclable plastic, force the plastic into a heated die, and cut-off the nuggets to a length of 5.1 cm (2 in.).

Twenty-two steady-state test runs with durations of either 10 or 20 min were performed to determine maximum Plastofuel™ production rate with two different types of plastic feedstock. Die temperatures ranged from 125°C to 220°C. Production rates ranged from 15.3 to 27.7 kg/h (33.7 to 61 lb/h). The maximum machine production rate was 27.6 kg/h (61 lb/h).

The system energy ratio was optimized by minimizing energy used to form the Plastofuel™ nuggets and maximizing the amount of Plastofuel™ formed. Automation contributed to both. Automation of the compaction, extrusion, and cutting processes nearly eliminated operator effort.

Machine feedback in the form of a load-sensing hydraulic signal was also critical to increase the system energy ratio. When the hydraulic cylinders encountered high resistance hydraulic pressure increased and flow decreased. Conversely, supply line pressure decreased and flow increased as the hydraulic cylinders encountered little resistance during their stroke. Finally, electrical energy consumption by the die assembly heaters was minimized using closed loop temperature control on five, independently operated temperature controllers.
Table 3. Test summary and energy ratios (Lawrence, 2007).

<table>
<thead>
<tr>
<th>Test Run</th>
<th>Feedstock Type</th>
<th>Die Temp. (°C)</th>
<th>Prod. Rate (kg/h)</th>
<th>Shredding Energy (kWh)</th>
<th>Electrical Energy (kWh)</th>
<th>Hydraulic Energy (kWh)</th>
<th>Energy in Plastofuel™ (kWh)</th>
<th>Energy Ratio (Energy Out / Energy In)</th>
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<tr>
<td>1</td>
<td>1</td>
<td>135</td>
<td>17.4</td>
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<td>2</td>
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REFERENCES
