FINAL REPORT

Shredded Waste Downdraft Gasifier for Overseas Contingency Operations Waste-to-Energy Conversion

SERDP Project WP-2235

JUNE 2015

Michael Cushman
Infoscitex Corporation

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
06-01-2015	Final Report	May 2011 - June 2015

4. TITLE AND SUBTITLE
Shredded Waste Downdraft Gasifier for Overseas Contingency Operations Waste to Energy Conversion

5a. CONTRACT NUMBER
W912HQ-12-C-0067

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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Reed, Matthew
Belcher, Jim
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5d. PROJECT NUMBER
WP-2235

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Infoscitex Corporation
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Littleton, MA 01460

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
SERDP Program Office
Bruce Sartwell
901 North Stuart Street, Suite 303
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The Department of Defense (DOD) has a strong interest and focused need to reduce the logistics tail associated with forward operations. Activities associated with mission sustainment at forward operating bases (FOBs) and combat outposts (COPs) present significant challenges with respect to fuel and water supply, and waste footprint management. Waste to energy conversion (WEC) systems present a promising option for managing waste burdens while providing supplemental energy/heat. While a number of gasification and pyrolysis-based WEC systems are currently under evaluation by the DOD, no system has been demonstrated to meet PM Force Sustainment Systems' (PM FSS) desire for a compact (8'x8'x20'), efficient (50% net chemical energy recovery), and robust (field-worthy, minimal operator interface) WEC system. To address the current need, Infoscitex Corporation (IST) proposed the development of a downdraft gasification system capable of processing shredded waste into clean-burning syngas. The overall objective of the proposed effort was to design, fabricate, and demonstrate a gasifier capable of reliably and efficiently converting shredded (single-stage), co-mingled (paper, food, plastic, wood) waste into syngas suitable for use in either a spark ignition or diesel cycle generator set.

15. SUBJECT TERMS
Waste-to-energy, gasification, thermal conversion, reactor design, plant design, distributed energy, waste management

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Matt Reed
U	U	U	UU	154	19b. TELEPHONE NUMBER *(Include area code)* 781-419-6379

Reset

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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LIST OF ACRONYMS

AFB	Air Force Base
CAD	Computer-Aided Design
COP	Combat Outpost
DOD	Department of Defense
ESTCP	Environmental Strategic Technology Certification Program
ESTOP	Emergency Stop
FID	Flame Ionization Detector
FOB	Forward Operating Base
GC	Gas Chromatograph
GEM	Green Energy Machine
I/O	Input/Output
ISO	International Organization for Standardization
IST	Infoscitex
MSW	Municipal Solid Waste
OFWEC	Onsite Field-feeding Waste to Energy Converter
PLC	Programmable Logic Controller
PM FSS	Product Manager Force Sustainment Systems
SERDP	Strategic Environmental Research and Development Program
SON	Statement of Need
STP	Standard Temperature and Pressure
SWP	Solid Waste Preprocessor
TCD	Thermal Conductivity Detector
TQG	Tactical Quiet Generator
VFD	Variable Frequency Drive
WEC	Waste to Energy Conversion

KEYWORDS

Waste-to-energy, gasification, thermal conversion, reactor design, plant design, distributed energy, waste management

ACKNOWLEDGEMENTS

This research was supported fully by the Department of Defense, through the Strategic Environmental Research and Development Program (SERDP).

The PI would like to acknowledge the efforts of the following individuals who contributed to the execution of this work:

- Infoscitex Corporation
  - Matthew Reed, Project Manager
  - James Belcher
  - David Montella
  - Leslie Sasa
  - Simeon Schlis
- Jenike & Johanson
  - Roger Barnum
  - Brian Pittenger
- MSW Power Corporation
  - Matt Young, co-Principal Investigator
  - Joe Abner
  - Steve Chase
  - Dave Rich

1 ABSTRACT

The Department of Defense (DOD) has a strong interest and focused need to reduce the logistics tail associated with forward operations. Activities associated with mission sustainment at forward operating bases (FOBs) and combat outposts (COPs) present significant challenges with respect to fuel and water supply, and waste footprint management. Waste to energy conversion (WEC) systems present a promising option for managing waste burdens while providing supplemental energy/heat. While a number of gasification and pyrolysis-based WEC systems are currently under evaluation by the DOD, no system has been demonstrated to meet PM Force Sustainment Systems' (PM FSS) desire for a compact (8'x8'x20'), efficient (50% net chemical energy recovery), and robust (field-worthy, minimal operator interface) WEC system. To address the current need, Infoscitex Corporation (IST) proposed the development of a downdraft gasification system capable of processing *shredded* waste into clean-burning syngas. The overall objective of the proposed effort was to design, fabricate, and demonstrate a gasifier capable of reliably and efficiently converting shredded (single-stage), co-mingled (paper, food, plastic, wood) waste into syngas suitable for use in either a spark ignition or diesel cycle generator set.

Key outcomes of this SERDP effort include:

- A diverging downdraft shredded waste gasifier was designed and fabricated. Wall taper, cross-sectional geometry, and height were arrived at to achieve mass flow at a targeted rate.
- Flow simulations were completed to model secondary air penetration within the system.
- The shredded waste gasifier was demonstrated in a laboratory environment to achieve bulk solids flow without stagnation due to bridging or arching. This was achieved with both paper/cardboard and food/plastic/paper/cardboard feedstock.
- A scaled-up diverging downdraft gasifier capable of processing three tons of mixed waste per day was designed.

2 OBJECTIVE

The overall objective of this effort was to design, fabricate, and characterize a gasifier capable of reliably and efficiently converting shredded (single-stage), co-mingled (paper, food, plastic, wood) waste into producer gas suitable for use in a diesel cycle generator set. Specifically, this effort aimed to identify reactor geometries and corresponding processing conditions best suited to enable waste-to-energy conversion system design with minimal preprocessing of the waste prior to conversion.

3 BACKGROUND

The primary requirements of waste to energy conversion systems for forward operating bases include:

- Dramatically reduce the footprint and logistics burden associated with waste management.
- Generate electricity from co-mingled waste.
- High thermal efficiency to reduce dependency on liquid fuel for on-site field uses.
- Deployable and compact to minimize logistics transportation support and on-site field set-up.
- Reliability with minimal operator and soldier interface, and minimal field system maintenance.

The proposed approach involved the use of a downdraft gasifier that is capable of producing a high energy, low tar producer gas from shredded co-mingled solid waste as the fuel feedstock. The producer gas will be fed into a diesel engine/generator, and together with diesel fuel, generate net electricity for on-site use. The selection of this type of gasifier and generator is directly related to satisfying the requirements of the field-operated WEC system.

3.1 Gasification

3.1.1 General Approaches

Downdraft co-current moving bed gasifiers are the most suitable to convert high volatility fuels (municipal solid waste, biomass) to low tar producer gas [1, 2] for use in generating power for a battalion-scale WEC operation. In these gasifiers, the primary gasification air is introduced at or above the oxidation zone in the gasifier and is pulled through the reactor by a vacuum pump. The shredded waste fuel flows in the same direction as the reaction air. The producer gas is removed at the bottom of the gasifier. The downdraft gasifier *produces much less tar* than any other gasifier because the volatiles are largely converted in the pyrolysis zone at the top of the reactor and then pass through the hot char gasification zone at the bottom of the gasifier, where they are further converted. Downdraft gasifiers have been limited in their ability to use unprocessed fuels, such as fluffy, low density materials because of excessive pressure drop across the gasifier. As a result, the solid fuel must be pelletized or briquetted before use in the gasifier. In most downdraft gasifiers, it is difficult to maintain uniform high temperatures over a given cross-sectional area, limiting the gasifier to a smaller cross-sectional area and lower power production.

Updraft (counter-current) moving gasifiers are used for coal gasification and with non-volatile fuels and have relatively low throughput rates. Air enters at the bottom of the gasifier and the producer gas leaves at the top, in a direction counter-current to the flow of the solid fuel particles. Updraft gasifiers utilize internal heat exchange, leading to low gas exit temperatures and resulting in high thermal efficiency. However, the low exiting gas temperature result in a significant tar content in the synthesis gas and are not suitable for energy production applications. *Fluidized bed gasifiers* are suitable for use in large scale energy production and with smaller particle feed stocks, without the need for extensive pre-processing. Air is blown into the reactor at a sufficient velocity to keep the solid particles in a state of suspension. The

bed is initially heated and the fuel particles are introduced at the bottom of the reactor and mixed with the hot bed material. The fuel is pyrolyzed very quickly and produces a large amount of gaseous material. The fluidized bed reactors are oversized compared to fixed bed gasifiers.

3.1.2 Producer Gas and Diesel Engine/Generators

IST has previously tested both spark ignition and diesel engines with producer gas and found that a diesel engine is more suitable for use with municipal solid waste (MSW)-type waste. Spark ignition engines are used when the energy content and composition of the producer gas are relatively constant, as with wood as a feedstock. When the energy content and composition of the feed stock is variable, such as with MSW, diesel fuel helps to supplement the producer gas and provide a reliable and constant supply of energy to sustain the engine cycle. Tests of the GEM WEC system have shown that the producer gas replaces more than 85-90% of the diesel fuel.

3.1.3 Shredded Waste Gasification

The development of a downdraft gasification system that uses shredded waste is not without its challenges. Gasification of shredded waste has only been done successfully in fluidized bed reactors that are bulky and used primarily for much higher shredded waste flow rates and energy production. Shredded waste, with a high surface to volume ratio, has very high wall friction for typical gasifier geometries (uniform diameter or tapered with its area decreasing in the direction of solids flow). This high friction retards the solids flow along the walls of the gasifier reactor, resulting in non-uniform solids funnel flow across the cross-sectional area and isolated regions of low permeability and excessively high temperatures. Funnel flow is a flow pattern in which solids flow in a channel formed within stagnant material. In addition, because of the regions of low permeability, a high pressure drop is required to pull the air flow through the length of the reactor and uniform gas flow is difficult to achieve across a given reactor cross-section. Secondary air is also needed to control the gas temperatures in the reactor to produce optimum pyrolysis, combustion and gasification in the gasifier. Secondary air is usually injected into the reactor normal to the direction of the solids flow. The non-uniform solids flow and low permeability result in poor penetration of the secondary air into the interior of the reactor.

The following sections discuss the proposed technical approach and the methods used to overcome the obstacles associated with developing a downdraft gasifier capable of processing shredded waste.

3.2 Design Approach for Small-Scale Deployable Gasification Systems

The municipal solid waste (MSW) is fed into a shredder and then densified in a compacting auger that increases the bulk density prior to entering the gasifier. The proposed gasifier configuration is a diverging cone that opens in the direction of the solids flow (Figure 1). All of the ash from the reactor is collected by the grate and is discharged through converging collectors to two grinders. A unique secondary gas injection system is proposed to enable more uniform air flow in a high pressure drop environment. Figure 1 illustrates the anticipated design of an improved downdraft gasifier, one based on the fundamental flow properties of its solids and gas

components. The diverging reaction sections are provided with tapered crossbeams (in the flow direction) and annuli for effective injection of secondary air without causing the bulk solids to be hung up in the reactor. The discharge section is designed for *bulk solids mass flow* to ensure that the velocity of the moving solids is uniform across any given cross-section of the gasifier without any regions of stagnant flow. The primary advantages of this system, compared to a more conventional downdraft gasifier with solid fuel pellets are:

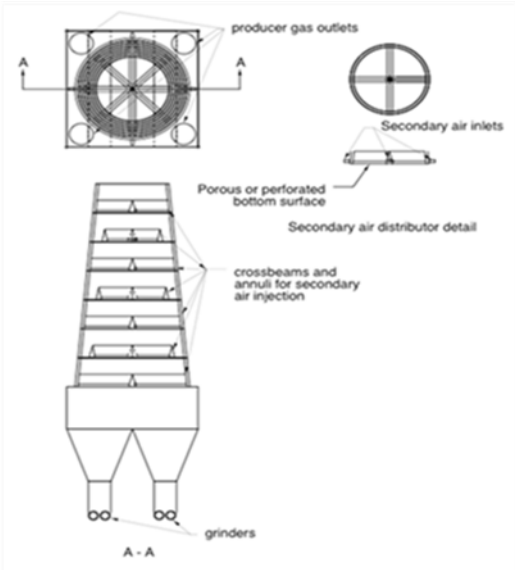


Figure 1. Proposed gasifier configuration with secondary air inlets.

- The diverging gasifer section reduces the friction between the shredded waste and the reactor surface, and reduces the potential for bulk solids flow problems, such as arching and rat-holing.
- Higher fuel (shredded MSW) surface area to volume ratio, resulting in much faster reaction kinetics to increase the conversion efficiency and reduce the reactor height and pressure drop from the primary air flow.
- Reduce the footprint and weight of the pre-processing system by eliminating a pelletizer, drier and non-ferrous metal separator.

The practical challenges to be addressed in design of the system were:

- More difficulty in achieving uniform gas flow in the reactor because of the higher pressure drop across shredded waste with primary and secondary air.
- More difficulty in achieving uniform flow across the reactor cross section because of the diverging area.
- Lower bulk density of shredded waste compared to pellets, resulting in a wider gasifier reactor and making it more difficult to achieve uniform bulk solids and gas flows.

3.2.1 Gasifier/Grate Design and Air Injection

Mass flow of the shredded waste solids in the reactor and grate and even distributions of primary and secondary air in the reactor are required to achieve optimum gasifier performance and are described below. Design considerations are given below.

Solids Flow in Gasifier and Grate
Bulk solids *mass flow* is required in the reactor and grate to achieve a uniform solids velocity and temperature over the cross-sectional area of the reactor. In mass flow, the entire bulk solids bed is in motion when char is discharged from the outlet of the reactor. For mass flow to occur in the cone configuration, the opening of the grate should be at least large enough to avoid blockages due to the formation of stable, cohesive arches, as well as 'mechanical' arches caused by interlocking of larger particles over the grate opening. The advantage of the diverging reactor is that it reduces the friction between the small shredded waste particles and the reactor surface and minimizes the potential for flow problems, such as arching.

In a downdraft gasifier, the solids flow through the reactor is controlled by the grate and not by the flow at the top of the reactor. The bulk solids flow through the grate must also be of the mass flow type. This occurs when the walls of the converging section of the reactor are steep enough and low enough in friction to allow char to flow along the walls. Mass flow guarantees complete discharge of the contents of the reactor at predictable flow rates. As shown in Figure 1, the ash will be discharged through two hoppers. This flow is similar to the more conventional reactor geometry in which the top of the reactor has a constant area (parallel walls) and the bottom of the reactor has converging walls; bulk solids flow occurs along the walls of the cylinder. This occurs when the walls of the converging section are steep enough and low enough in friction to allow char to flow along the walls. Wall friction is measured by a method described in ASTM Standard D-6128 [3], where a sample of bulk material is placed inside a retaining ring on a coupon of wall material, various loads are applied, and the shear force required to cause the bulk material to slide along the wall surface is measured. Typical wall friction data obtained at 600°C for a sample of MSW Power Corp. gasifier char on refractory are shown in Figure 2. Knowing the char's wall friction (and internal friction, which is obtained by shear cell testing), the slope of the walls of the converging section of the reactor can be calculated using a method developed by Jenike [4].

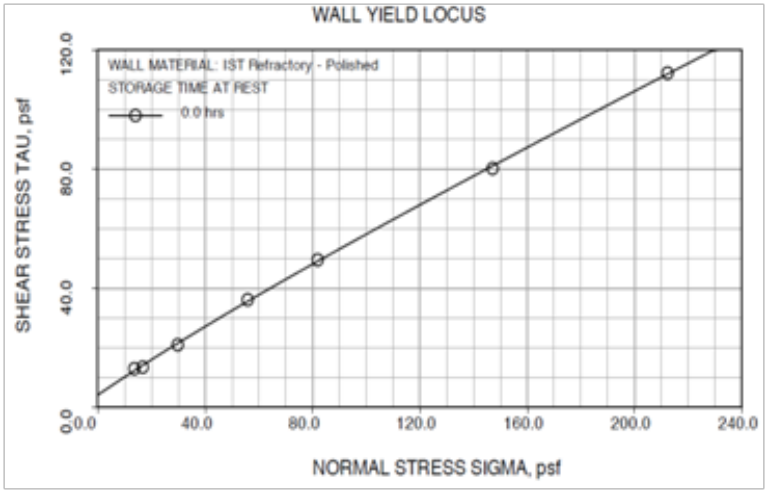


Figure 2. Wall friction data for IST Energy gasifier at 600°C.

Prior to this effort, IST and MSW Power worked to optimize bulk solids flow on a three-ton per day pellet-fed gasifier. Flow property tests were performed on samples of municipal solid waste generated by the GEM pre-processing system (pellets), char from within the GEM gasifier, and char/ash fines discharged from the GEM gasifier and recommendations were made to modify the gasifier and grate, primarily by tapering (converging) the reactor and grate geometries in the bulk solids flow direction, resulting in solids *mass flow.* These recommendations resulted in a number of improvements over the initial gasifier performance:

- Bulk solids moved continuously and uniformly throughout the gasifier and grate.
- The gasifier grate operated continuously and the bottom ash removal rate was 3-5% of the pellet feed rate.
- Design values of the pressure drop of the air across the reactor were achieved.
- Temperatures throughout the reactor, at a given cross section and through the length of the reactor, reached steady state and were consistent from run to run.
- Hot spots in the reactor were eliminated.
- When temperatures in the reduction zone of the gasifier were in the target range, very little tar was found in the particulate filters.

Primary and Secondary Air Injection

The gas temperature profile in the gasifier must be controlled in order to keep the composition of the producer gas generated in the gasifier and to reduce the levels of tar that can foul downstream processing equipment and the engine/generator. Primary air must be allowed to flow uniformly through the reactor without channeling and without an excessive pressure drop, while secondary air must also be injected as uniformly as possible across the cross section of the reactor to reach the fuel in the center of the reactor. One of the primary advantages of the proposed gasifier system is that the high surface to volume ratio of the shredded waste will result in faster kinetics than pelletized waste, thereby reducing the reactor height and pressure drop through the reactor. Secondary air injection through nozzles placed around the periphery of the gasifier are less than ideal since the air is injected locally as high-velocity streams, and therefore much of the secondary air bypasses the solids. Improvements in gas uniformity can be achieved instead by

injecting the air into the bed of solids via an annulus and a set of tapered crossbeams (Figure 1). In such a design, secondary air can be injected both circumferentially and radially, leading to improved uniformity compared to nozzles and other gas injection methods. To minimize the potential for flow hang-ups due to, for example, arching of solids inside the gasifier, the crossbeams and annuli should be placed inside diverging conical sections instead of a constant-diameter cylinder and the crossbeams tapered in the solids flow direction (see Figure 1).

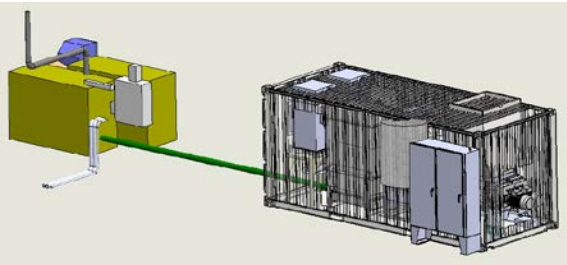
3.2.2 Reduction in WEC Footprint

The use of shredded waste in a downdraft gasifier eliminates the need for a pelletizer and a non-ferrous metals separator as used in MSW Power WEC GEM system and reduces the field system maintenance and soldier interface. Without metals separation, hard and dense non-ferrous metals found in MSW can jam the rollers of the pelletizer and should be removed from the pelletizer, requiring extensive maintenance and costly downtime.

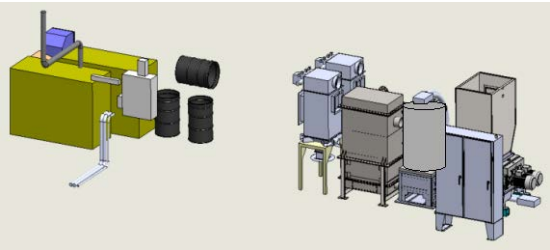
A dryer, normally placed between the shredder and pelletizer, can also be eliminated from the WEC system, especially at the low moisture content of the feedstock (16 %) specified in the OFWEC Energy Balance. The IST WEC system has successfully gasified pellets with a moisture content of 12%. Moisture is vaporized from the waste feed stock in the pyrolysis zone and partially used in the downstream combustion and gasification reactions. Shredded waste, with a high surface to volume ratio, will allow more extensive drying in the pyrolysis zone than is observed for pellets. Moisture still has to be to be removed from the producer gas prior to burning in the engine generator. A small heat exchanger is presently used to condense the moisture and the waste heat from the generator will vaporize the liquid in a small tank. Tars and other contaminants will fall to the bottom of the tank during evaporation and will need to be periodically removed. This same system can be used for higher feedstock moisture content. The effect of the MSW moisture content on the quality of the producer gas and the ability to remove the water prior to burning the producer gas will be assessed during the test program.

For the purpose of comparison, the present 3 tons per day IST GEM WEC system (with a pellet feedstock to the gasifier), that was evaluated at Edwards AFB under an ESTCP Demonstration program, is shipped in an 8’6” wide x 9’6” tall x 40’ long ISO container. The engine/generator is shipped in a separate 8’ wide x 8’ tall x 20’ long container. Figure 3 shows a CAD drawing of the proposed shredded waste gasifier GEM WEC system in a 20 ft ISO container without a pelletizer, drier and metals separator and supporting conveyor systems. Equipment components in the WEC system include a shredder (shown with hopper, right rear), gasifier and grate (right front center), heat exchanger (left front center) and particulate filters (left rear). The heat exchanger used to condense the moisture from the producer gas is not shown, but can easily be placed in the generator container. Further reductions can be made in the footprint of the downstream gas conditioning system (heat exchanger and particulate filters). Two standard DoD 60 kw tactical quiet generators (TQG) have been included in the generator ISO container. It appears from this preliminary drawing that the shredded waste gasifier WEC system with the generators can fit into two 20 ft ISO containers. In practice, it is expected that TQGs already in-use at the FOB would be available for integration with the WEC system, thus reducing the need for shipment of a genset container, and reducing overall shipping footprint to a single 20-ft

container. This conclusion will be validated based on the results of the proposed experimental test plan and the design of a shredded waste WEC system in Task 5.



A. Generators (Left) and Shredded Waste Gasifier WEC System (right) in ISO Container



B. System components (without ISO container)

Figure 3. Layout of 3 tons per day shredded waste gasifier WEC system in two 20 ft ISO containers.

4 MATERIALS AND METHODS

The technical program was focused on developing a downdraft gasification system capable of processing shredded waste into clean-burning producer gas with the objective of supplying a base camp with electricity and heat, while at the same time substantially reducing the footprint of the waste pre-processing system. To accomplish this, efforts were focused on the development of a flow optimized downdraft gasifier. IST's stratified downdraft gasifier was chosen as a baseline against which to develop enhancements. There were six primary tasks to the research and development effort, all executed in an iterated fashion until program completion:

1. Define needs
2. Material flow characterization
3. Air flow modeling
4. Gasifier modification design/fabrication
5. Experimentation
6. Analyze and Evaluate Results

Details of the overall approach are shown schematically in Figure 4.

4.1 Definition of Needs

A needs assessment was performed to ensure the technical effort was constructed to be best positioned to yield impactful outcomes. Based on the SERDP statement of need (SON) and prior experience developing military waste to energy conversion systems, the following requirements were defined:

1. Design a mass flow gasifier to minimize/abate the formation of rat holes and arching.
2. Design gasifier and secondary air injection configuration to efficiently process and convert shredded waste to producer gas.
3. Demonstrate gasifier reactor in the laboratory.
4. Design complete WEC gasification system to meet footprint requirements.
5. Reduce weight and footprint of preprocessing system by eliminating pelletizer, drier and non-ferrous metal separator.
6. Characterize shredded waste in gasifier with respect to bulk flow properties.
7. Integrate prototype gasification system with downstream gas conditioning system and engine/electric generator.
8. Instrument gasification, downstream gas conditioner, and energy/generator subsystems to quantify performance and provide detailed mass and energy balance.
9. Characterize performance of prototype gasification system.
10. Model pyrolysis and gasification zones in gasifier reactor and determine temperature and gas composition profiles.
11. Redesign prototype gasifier to improve gasifier operability and conversion efficiency.
12. Design a three-ton per day full-scale shredded waste downdraft gasification system.

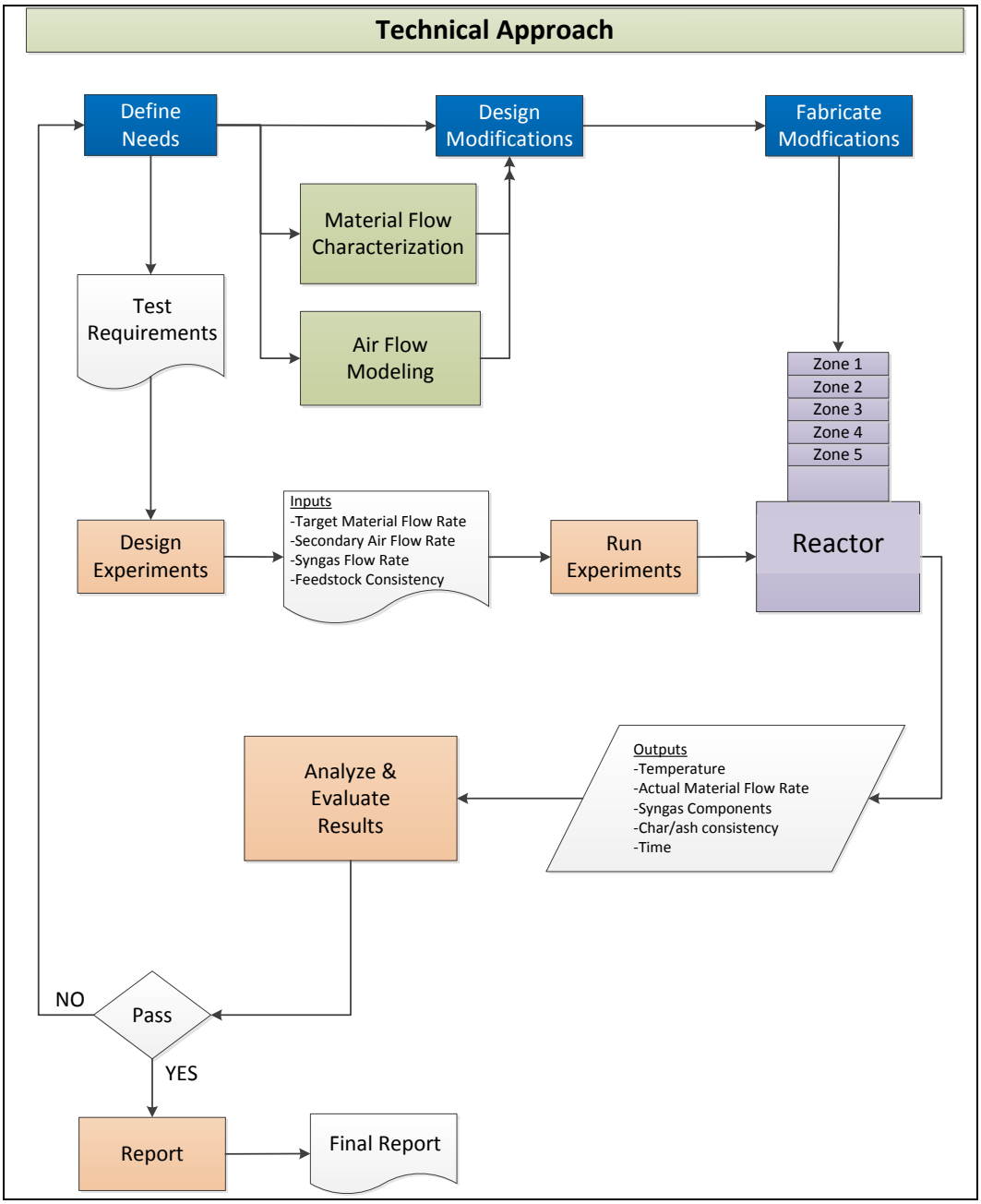


Figure 4. Technical approach.

4.2 Material Flow Characterization

In a downdraft gasifier, the material flow through the reactor is controlled by a grate at the exit of the gasifier and not by the flow at the top of the reactor. Bulk solids mass flow is required both in the reactor and grate to achieve a uniform solids velocity and temperature over the cross sectional area of the reactor. In mass flow, the entire bulk solids bed should be in motion when char is charged from the outlet of the reactor. Mass flow guarantees complete discharge of the content of the reactor at predictable flow rates. An additional requirement is that obstructions in the solids flow cannot develop. Flow property tests were performed on (a) shredded food waste

(44.5% by weight, paper (42.2%) and plastics (13.3%) at different moisture contents and (b) char/ash from a downdraft gasifier. Data was obtained for both unpolished and polished refractory that will be used as the walls of the gasifier. Tests included:

- Cohesive strength and physical modeling - to determine minimum outlet size to prevent arching and to confirm that gas injection and control devices will not interfere with solids flow.
- Wall friction - to determine wall materials and geometry to be used to allow solids mass flow.
- Compressibility – to provide relationship between consolidated pressure and bulk density and provide residence time calculations.
- Permeability – provides relationship between gas velocity and pressure drop for design of secondary air distribution system.

Shredded waste samples, as summarized in Table 1, were prepared for the purpose of assessing how the shredded waste would flow through a gasifier.

Table 1. Shredded waste samples prepared for flow property testing.

	Shredded Waste 1	**Shredded Waste 3**	**Shredded Waste 4**
Shred size, mm	20	20	15
Composition	Ft. Polk	Ft. Polk	Ft. Polk
Moisture content, %	10	20	10

Photos of each sample type are provided in Figures 5-7.

Tests were run to determine the cohesive strength of the material (used for critical arching and ratholing dimensions), particle interlocking (used to evaluate particle size and shape for the potential of interlocking arching through narrow gasifier sections), wall friction angles (used for calculating mass flow hopper angles), permeability (used to determine critical steady-state discharge rates), and bulk density/consolidating pressure relationship. Cohesive strength and wall friction tests were run for continuous flow conditions only at room temperature (72°F).

In addition to shredded MSW, char ash produced from the conversion of MSW was tested to assess the cohesive strength, wall friction angles, permeability, and bulk density/consolidating pressure relationship for char ash. As the feedstock under goes significant physical changes as it progresses through a gasifier, it's critical to understand how the mass flow properties of the material changes. Figure 2 shows some typical wall friction data obtained for char/ash at 850°C on a polished refractory. This data was used to calculate the slope of the walls of the gasifier.

Figure 5. Shredded waste sample #1.

Figure 6. Shredded waste sample #3.

Figure 7. Shredded waste sample #4.

Based on the acquired material flow data, key objectives and design requirements for the prototype gasifier were specified as follows:

1. Gasifier walls tapered at 5 degrees.
2. Increasing area from the inlet to the outlet of the reactor.
3. Gasifier inlet rectangular cross sectional area of 102 cm x 15.2 cm (4” x 6”).
4. Gasifier height of 61.0 cm (24”).
5. Polished refractory.

The diverging tapered walls of the gasifier reduce the friction between the shredded waste and the reactor surfaces, thus reducing the potential for bulk solids flow problems such as arching and rat-holing. The rectangular design reduces the distance of secondary air coverage, maximizing its reach without extending nozzles into the reactor. Finally, the gasifier size was specified to handle a shredded waste flow of 7.6 kg/hr (16.7 lb/hr) and a syngas flow rate of 0.61 m3/min (20.0 ft^3/min).

4.3 Air Flow Modeling

For high conversion efficiency, secondary air should penetrate to the center of the gasifier, reacting with as much of the waste in the pyrolysis zone as possible. Shredded waste has a low permeability (high resistance) to gas flow compared to pellets and the extent of the secondary air gas penetration into the gasifier can be limiting. SolidWorks Flow Simulation analyses [5] were carried out on the gasifier configuration shown in Figure 8 to determine the penetration distance of the secondary air into the solid waste as a function of the following operating conditions:

1. Secondary air flow as a percentage of the total syngas flow
2. Waste permeability (resistance)
3. Nozzle diameter (flow velocity)
4. Mass flow per ring
5. Number of secondary air flow rings

This model does not take into account mixing between the solid waste and the secondary flows. The penetration distance was determined by the distance of the limiting streamline from the wall of the gasifier.

The solid waste was considered to be porous, with the permeability determined by the pressure drop along the length of the reactor. The gas flow in the reactor is defined by Darcy's Law [6]:

$$m = -A*\Delta p/(k*L)$$

where:

- m =gas mass flow, kg/sec
- A = cross-sectional area in direction of flow, m2
- Δp = pressure difference in direction of flow, kg/m2
- L = length in direction of flow, m
- k = porous medium flow resistance, sec/m

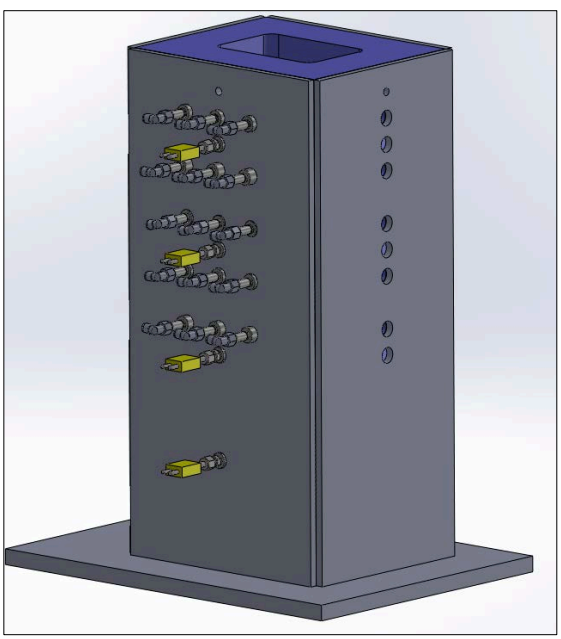


Figure 8. Downdraft Gasifier.

For high resistance or low permeability and for a fixed pressure gradient, the mass flow through the porous medium is very low. Conversely, for a fixed mass flow rate and high resistance, the pressure gradient is very large. The resistance coefficient was calculated as 336 sec/m for a full-

scale WEC unit using pelletized waste. Based on pressure drop measurements taken during testing of the shredded waste gasifier, the resistance was calculated to be 2200 sec/m, about 6.5 times that of the flow resistance in the pelletized gasifier.

Figure 9 shows the secondary air streamlines through the center planes of the gasifier for a given flow resistance. The secondary air is coming in through the first ring of injection ports, 6.4 cm (2.50”) from the top of the inlet to the reactor. There are eight 3.2 mm (0.125”) injection ports in the first ring with three ports on each on the long faces of the gasifier and one port on each of the short sides. Figure 10 shows the secondary air streamlines through planes parallel to the top face of the gasifier. In Figure 10, the limiting streamline from the injection port is initially parallel to the plane of the injection ring and then bends towards the axis of the gasifier, reaching a maximum distance from the injection port slightly below the plane of the injection ring.

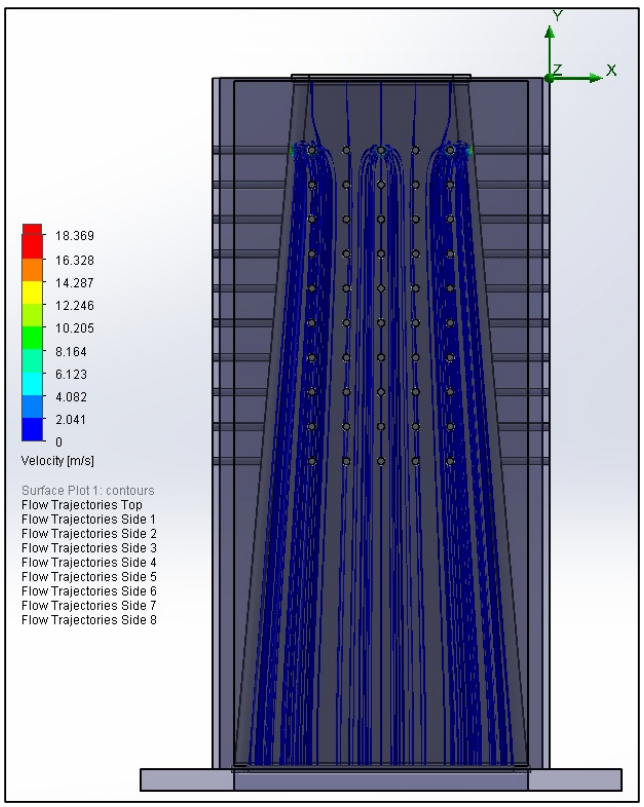


Figure 9. Secondary Air Streamlines (Side view).

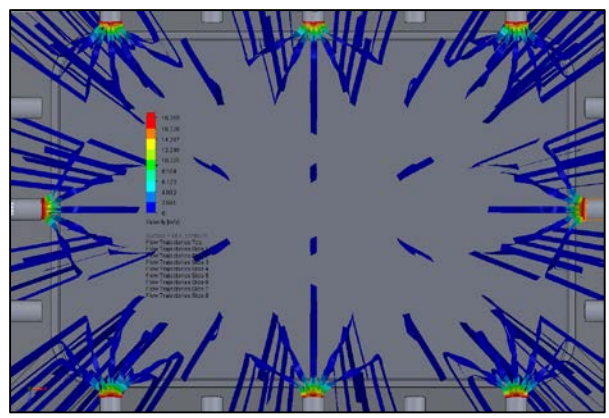


Figure 10. Secondary Air Streamlines (Top view).

In Figure 11, the penetration distance is plotted as a function of secondary air (as a percent of the producer gas flow rate) for a relatively high flow resistance of $3.36*10^2$ sec/m. The secondary air is injected from the first ring of injection ports (2.5” from the inlet). The distance from the injection port on the long side of the gasifier to the center of the gasifier is 2.2 in. At this high resistance, there is very little penetration of the secondary air into the center of the gasifier, regardless of the secondary air injection velocity. In Figure 12, the penetration distance is shown

as a function of the resistance for a constant secondary air flow rate. At relatively high flow resistances, the penetration distance is relatively constant (~1.4 inches), about 33% of the distance to the center of the gasifier. As the flow resistance is reduced, the penetration distance increases until it reaches the center of the gasifier. At a lower flow resistance and for a constant injection flow rate, the penetration distance increases with decreasing nozzle diameter or increasing injection velocity.

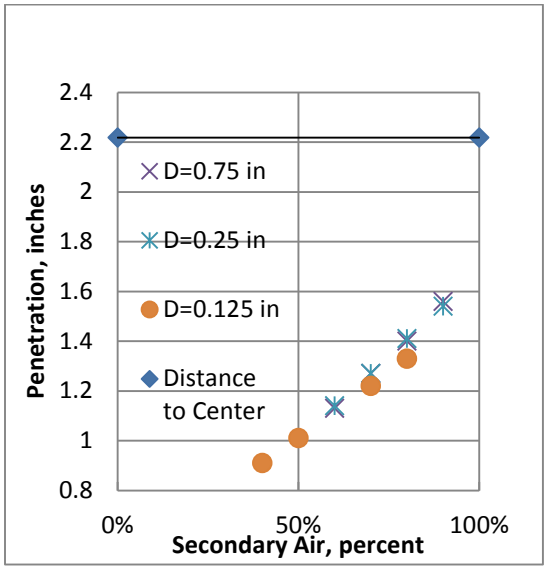


Figure 11. Effect of Secondary Air % on penetration.

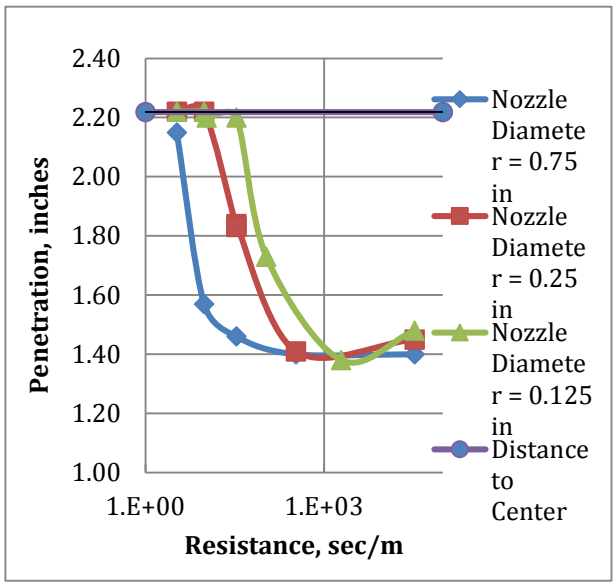


Figure 12. Effect of Resistance on penetration.

4.4 Gasifier Modification Design/Fabrication

In order to optimally process municipal solid waste in a downdraft gasifier several key operating functions must be met. The most important functions are:

- Consistent and controllable pressure drop across the reactor
- Controlled ash discharge
- Controlled syngas production
- Controlled secondary air injection rates
- Uniform particle flow

In order to produce a low tar syngas while maximizing energy content of the gas, the downdraft gasifier must allow for the following conditions:

- A pyrolysis zone in which volatile matter can be vaporized from the solid material with minimal oxygen. Ideally this reaction occurs between 400 and 600°C.
- A combustion zone in which the volatile matter from the pyrolysis reaction can be combusted to form carbon dioxide and water vapor while continuing to extract carbon

from the solid material. This reaction should occur at temperatures exceeding 900°C and ideally around 1000°C. The solid material should only contain fixed carbon (char).

- A reduction zone in which the hot char from the combustion zone interacts with carbon dioxide and water vapor in the absence of oxygen to produce hydrogen and carbon monoxide gases. This reaction occurs at temperatures around 750°C.

In order to achieve these conditions, the feedstock must meet certain requirements. Those conditions are:

- A moisture content below 20% by weight.
- A particle size that reacts at the rate in which the velocity of that particle reaches each zone with the correct properties. For example, the feedstock particle should have all the volatile matter removed from it prior to reaching the reduction zone, but the particle should not have been stripped of all its fixed carbon. If that occurs, only ash will be present in the reduction zone which will not act as a catalyst for the reduction zone.
- A permeability rate that allows for a consistent and low pressure drop across the reactor (3-5" WC). Additionally, the feedstock permeability should allow for penetration of secondary air that can evenly distribute throughout the cross-section of the reactor.
- Low coefficient of friction to allow for mass flow conditions to occur in the reactor. The higher the coefficient of friction the steeper the walls must be to produce mass flow conditions. In some instances, the coefficient of friction is so high that diverging walls must be used.
- Low mechanical interlocking rate, which allows the material to flow uniformly without bridging.
- Uniformity in the feedstock helps control the kinetic rates across each zone.
- Feedstock density helps to maximize energy production in a given reactor volume.
- Particle size.

Post gasifier, numerous operations are required to condition the gas. First, a shell and tube heat exchanger constructed out of stainless steel material is required to cool the hot syngas. This operation should be done first so that lower cost operations could be used downstream. The syngas could be cooled using water or air as the cooling media. Thermocouples should be placed at all inlets and outlets (4 in total) and a flowmeter should be installed on the cooling media. This will allow for analysis of the thermal performance of the heat exchanger. Additionally, the pressure drop across the heat exchanger should be monitored for fouling.

A particle filtration unit, such as a baghouse or cartridge filter, is required to remove any entrained char/ash and tar from the gas stream. The pressure drop along the filter should be monitored to determine if and when the filter is clogged with material.

A high pressure blower is required to be able to pull vacuum on the entire system while hitting the targeted syngas flowrate (15-30 CFM in this case). The blower should be able to pull 50" of water column at the upper flowrate target. A regenerative blower is commonly used for this scenario. A pressure sensor should be located just before the suction side of the blower to measure the full vacuum being pulled by the blower. Additionally, a variable frequency drive (VFD) should be used to control the blower speed.

A rotameter should be located after the reactor blower to measure syngas flowrate. A thermocouple right before the rotameter should be used to account for density differences caused by elevated temperatures in the gas. All data should be corrected to STP.

Figure 13 shows the gasifier system and downstream producer gas conditioning system. The gasifier was instrumented with thermocouples, pressure gauges, and flow meters. An electronically controlled vibrating grate was installed at the exit of the gasifier to control the waste flow through the gasifier and to remove char and ash. A heat exchanger to cool the producer gas (syngas) and a filter system to remove tars and other particulates were placed downstream of the grate (Figure 13). The producer gas was sampled downstream of the filters in syringes and its composition determined by gas chromatography.

A vacuum pump (blower) located downstream of the filters is the primary gas mover for the system. Five rings of secondary air injection ports were installed along the length of the gasifier, with the top three rings placed in and near the pyrolysis zone. Eight secondary air injection ports were installed in each ring; three ports each in the front and back faces of the gasifier and one port each on the side faces. Secondary air was injected through the ports normal to the walls of the gasifier. The air flow rate at each ring was independently controlled, as was the producer gas flow through the vacuum pump. The differential between total gas being moved by the blower from the amount of secondary air injected as well as the producer gas produced by the gasification of the waste is the amount of primary air added to the reactor through the top opening.

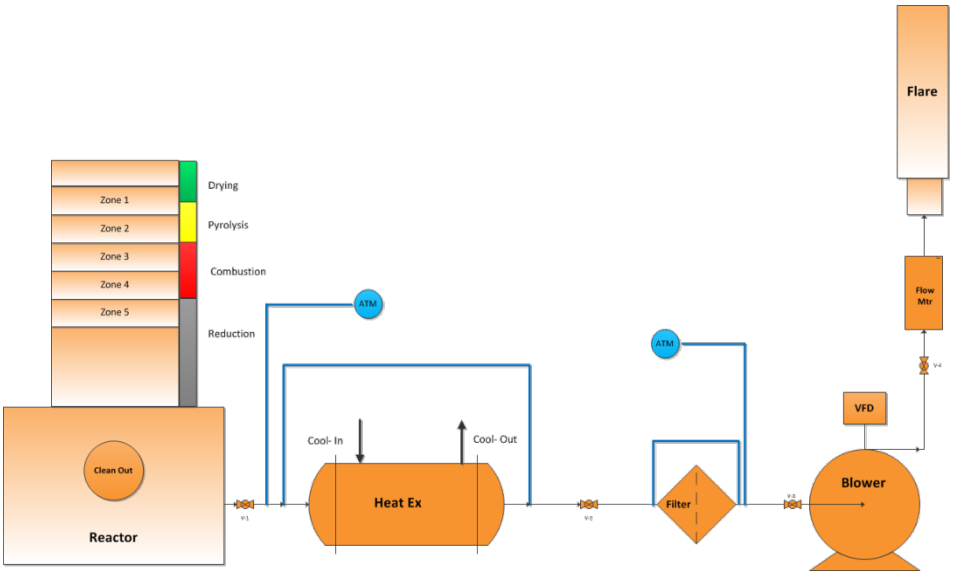


Figure 13. Gasifier and downstream producer gas conditioning system.

A small scale gasifier was fabricated to perform testing (Figure 14). First, the fire tube shell was constructed using carbon steel plates with 3/8" thickness. The plates were cut to the right dimensions and a CNC machine was programmed to insert the nozzle and thermocouple locations. The four sides were clamped together using an angle clamp to ensure perpendicularity between the faces and a full weld was added to each seam. Next, the base was cut to size (3/4"

thick carbon steel plate) and the discharge opening was plasma cut from the center and the mounting holes were located by the CNC machine. The plate was placed under the side walls and fully welded together.

Figure 14. Shredded waste gasifier fire tube shell.

The refractory was formed by placing a plastic mold, which was machined to the correct wall angles, into the fire tube structure (Figures 15 and 16). Steel rods that were coated in oil were passed through each opening in the steel walls to form the nozzles and thermocouple ports. Using the vendor's instructions, R-30 Express refractory material was formulated via mixing of dry product and water. Using a vibratory stick, the refractory was well mixed and poured between the walls and the form. Again the vibrating stick was used to remove any air bubbles in the refractory. It was then soft cured for 24 hours before the plastic mold and rods were removed. Another 24 hours was used to cure the refractory.

Figure 15. Side view of gasifier shell with refractory.

Figure 16. Inside of gasifier shell with refractory.

The reactor base was constructed using ½" thick carbon steel plates (Figure 17). The necessary holes were machined into each face and the structure was fully welded together. Before the top was added to the base, CS85 high temperature board insulation and the grate were installed.

Figure 17. Reactor base with insulation and grate visible.

Once the insulation, grate and poking rod were installed, the base top plate was welded on (Figure 18). The base top plate was machined and ¾"-12 by 4" long bolts were welded into it as studs. The head of the bolts were removed to create a smooth bottom surface to mate with the base walls. The discharge opening in the base top plate was formed by a plasma cutter. The entire top plate was fully welded to the base frame.

Woven fiberglass gasket material was placed between the reactor base and fire tube assembly before they were coupled together. All secondary air nozzles and thermocouple ports had their couplings welded to the openings in the fire tube. A handle was added to the top for transportability reasons. The completed gasifier is shown in Figure 19.

Once the gasifier was fabricated, a secondary air manifold system was designed and fabricated. The system is designed to control inlet air pressure and flowrate through eight different nozzles in each zone. An air compressor was utilized to provide the air.

The flare was designed and constructed in order to reduce flame height. A 1" to 4" coupling formed the body of the flare. 1" schedule 40 pipe with threads on one end was welded to the coupling so that it could be threaded into the blower piping. ¼" schedule 40 pipe nipples were added to the 4" section of the coupling and welded in tangentially to the inner diameter. This

will allow for air to mix with the gas in the flare. These ports will also allow an operator to ignite the flare with a torch. Lastly a 6” double walled chimney pipe will act as the flare shroud.

Figure 18. Reactor base with top plate.

Figure 19. Completed shredded waste gasifier.

Figure 20 shows the experimental facility in the laboratory. Prior to starting a test run, char was used to start up the gasifier. When the temperature in the top portion of the gasifier reached 800 to 900°C, shredded feedstock consisting of either paper/cardboard or mixed waste (paper, cardboard, food and plastic) with a moisture content of 10% was manually fed into the gasifier. The weight of the shred was recorded as a function of time. An electronically controlled vibrating grate was used to control the waste flow through the gasifier and to remove char and ash. The producer gas flow rate was manually set, monitored intermittently, and adjusted periodically with changes in the waste feedstock flow rate. The secondary air flow rates were

also manually set and recorded on a data sheet. For the test program, secondary air was injected through ports in the walls in the top three ring positions of the gasifier (2.5, 5.0 and 7.5 inches). The diameter of the injection ports were 0.269 inches (6.83 mm). For two tests, air was injected into a tube placed across the width of the gasifier through two holes of diameter 0.094 inches (2.38 mm) facing downward; secondary air was also injected through some of the sidewall air injection ports. The gasifier, downstream heat exchanger, filter, and blower temperatures and pressures were electronically monitored and recorded at a 1 Hz rate from system start-up to shut down. In the event of a backdraft from the gasifier, the secondary air flows were reduced until the backdraft disappeared.

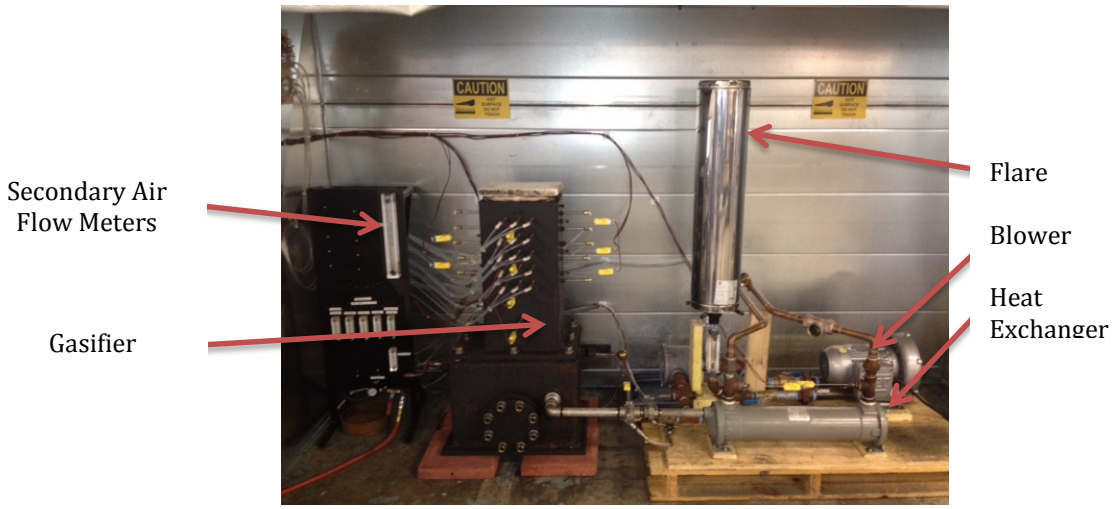


Figure 20. Photograph of downdraft gasifier laboratory facility.

The producer gas was sampled via a collection port immediately upstream from a downstream flare. A syringe was connected to the port, the gas was allowed to fill the tube for approximately 20 to 30 seconds to ensure the syringe was completely filled with producer gas, and then the syringe was capped. Three samples were taken for each set of test conditions. The collected gas was injected into a SRI 8610 Gas Chromatograph (GC) to perform compositional analysis. A methanizer equipped flame ionization detector (FID) was utilized to measure the concentrations of carbon monoxide, carbon dioxide, and methane, while a thermal conductivity detector (TCD) was utilized to measure the concentrations of nitrogen, hydrogen, and oxygen. The average of the samples was used to determine the producer gas energy.

The operation of the downdraft gasifier was guided by an equilibrium analysis of the gasification process. In the gasification zone, three reactions dominate [2,7,8]:

Boudouard reaction: $\text{Char} + CO_2 \rightarrow 2CO$, $\Delta H = +40{,}778$ kcal/mol
Water Gas Reaction: $\text{Char} + H_2O \rightarrow CO + H_2$, $\Delta H = +32{,}472$ kcal/mol
Water Gas Shift Reaction: $H_2O + CO \rightarrow H_2 + CO_2$, $\Delta H = -8{,}306$ kcal/mol

The char gasification zone is assumed to be adiabatic and the water gas shift reaction is assumed to be at equilibrium [7,8]. Table 2 shows the composition and ultimate analyses of the three waste streams used in the test program. The ultimate analysis for the paper/cardboard waste is

given in [4]; the mixed waste ultimate analyses were determined experimentally by Hazen Research, Inc. (Golden, CO). The equilibrium results are shown in Figure 21 and are based on the ultimate analysis as input. The equilibrium adiabatic gas temperatures and producer gas energies are also shown in Table 2 and Figure 21. This equilibrium model was used to determine how closely the test results approached equilibrium.

Table 2. Waste composition, ultimate analysis and equilibrium adiabatic gas conditions.

	Paper/Cardboard	**Mixed Waste # 1**	**Mixed Waste # 2**
Composition			
Paper, wt %	50	22	22
Cardboard, wt %	50	22	22
Food, wt %	-	38	33
Plastic, wt %	-	13	13
Added moisture, wt %	-	5	10
Ultimate Analysis, dry, wt %			
Moisture	0	0	0
Carbon	43.4	57.45	49.33
Hydrogen	5.8	7.51	6.13
Nitrogen	0.3	0.34	0.03
Sulfur	0.2	0.02	0.12
Ash	6.0	5.62	4.68
Oxygen	44.3	29.02	39.71
Total	100.0	100.00	100.00
Adiabatic Gas Temperature, °K	968	1027	1002
Producer Gas Energy			
BTU/ft^3	167	166	174
kJ/m^3	$6.22*10^3$	$6.18*10^3$	$6.48*10^3$

The objectives of the test program were to determine if (a) the gasifier design resulted in bulk solids mass flow and (b) the secondary air configurations that resulted in high producer gas energy. The producer gas energy was determined from the GC analysis for hydrogen, carbon monoxide and methane. The maximum temperature was determined from the data set and was taken to be the char combustion temperature just below the flaming pyrolysis zone in the gasifier, where the solid waste and the pyrolysis vapor is combusted by oxygen, producing CO_2 and water. The adiabatic char gasification temperature was taken near the bottom of the gasifier, where char is converted to ash.

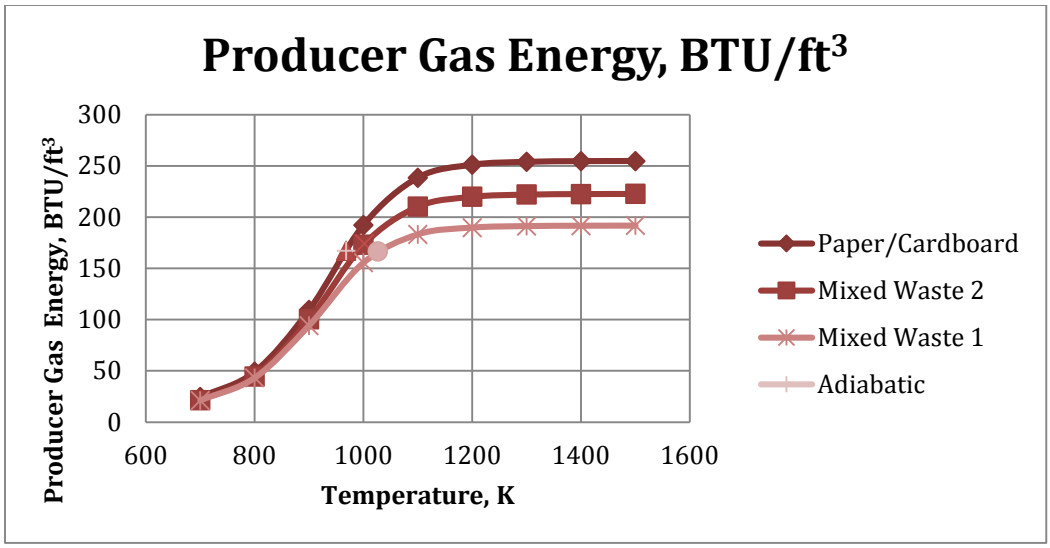


Figure 21. Equilibrium conditions for waste streams used during the test program. Filled circles indicate adiabatic conditions.

4.5 Experimentation

In order to define the design of experiments, it was necessary to identify the key outputs that will define the reactor performance. For this system, the major output data that would be collected and analyzed are:

- Syngas composition
- Syngas tar/moisture content
- Ash output
- Solid fuel flowrate
- Syngas flowrate

The major output data would be collected and analyzed according to Table 3.

The key variables that will be evaluated for testing are provided in Table 4.

In order to properly test each parameter and its effect on the system performance outlined in the output data section, each variable was to be tested while the others were held constant.

The solid waste composition will be a little bit more difficult to evaluate, therefore, testing should be started with single shredded source (such as paper) to optimize the conditions. The final composition should copy the results from the LIA study for CB waste compositions (Figure 22 and Table 5).

Table 3. Major output data for test program.

Output	Collection Method	Analysis Method
Syngas Composition	Collecting syngas from the positive pressure side of pump, using a gas collection device for temporary storage.	Utilize Gas Chromatography using a TCD and FID to detect CO, CO_2, H_2, CH_4, N_2 and O_2.
Syngas Tar/Moisture content	Collect a known volume of gas and process through an impinge train where the first three impingers contain solvent that will capture tars and the last three are chilled to condensate moisture.	Measure the weight difference in impingers to quantify the amount of tar and moisture collected. Send collected tar samples to third party for analysis of the different tar constituents.
Ash output	Collect all ash from the ash collection bin from each run.	Measure the before and after weight of the bin along with the solid waste throughput (and char start up weight) and duration of test to calculate % reduction and ash flowrate.
Solid fuel flowrate	Writing down weight added to the system for each charge and notating the time in the test of each charge.	Calculate the total weight added over the duration of waste being added.
Syngas flowrate	Recording the syngas flowrate indicated by an inline flowmeter like a rotameter.	Plot syngas flowrate over time to match up with other secondary data collected.

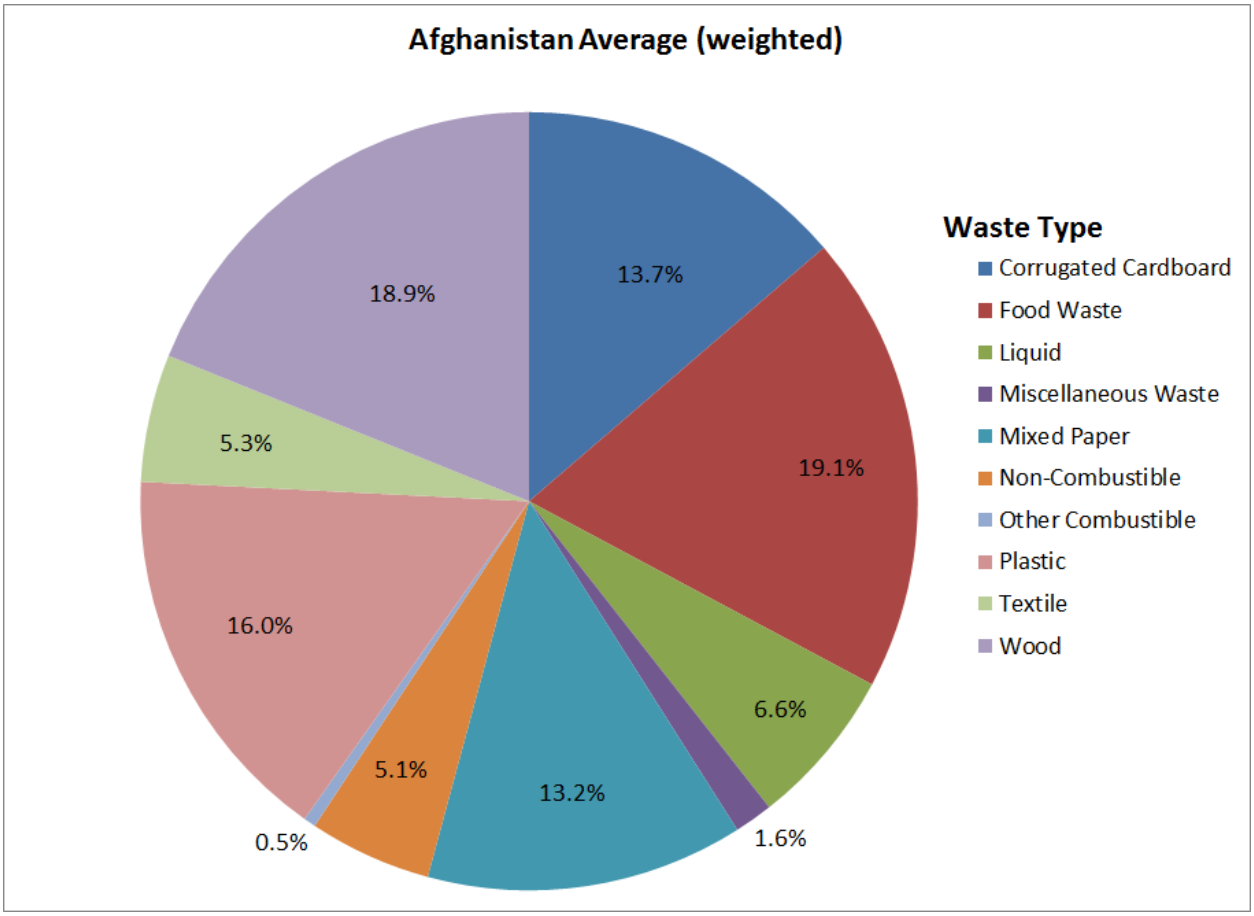


Figure 22. Summary of waste composition from LIA study.

Table 4. Key variables for test program.

Operating Variable	Relationship
Syngas flowrate to total secondary air ratio	The higher the syngas to total secondary air ratio is the higher the temperature the pyrolysis chamber will be and the cooler the combustion chamber will be. The goal is to define a ratio that allows for a pyrolysis temperature between 400-600°C and a combustion temperature of 900°C or greater for a given (fixed) solid fuel flowrate.
Secondary air distribution ratio	Understanding how much secondary air into each zone given a fixed syngas flowrate to total secondary air ratio will help zone in on the ideal operating conditions for the pyrolysis and combustion zone for a given solid fuel flowrate.
Solid Fuel flowrate	The solid fuel flowrate will impact reactor temperatures, and energy density/quality. The higher the flowrate, the less retention time in the reactor causing cooler conditions while leaving significant unprocessed material behind. Too slow of a solid fuel flowrate will cause kinetics to occur faster, reducing the ability to convert Carbon Dioxide and Water Vapor to Carbon Monoxide and Hydrogen.
Grate Speed	The grate speed controls how much material is being processed through the reactor. The faster the speed the faster the ash flowrate will be. Too fast and it will speed up the retention time of the material in the reactor, and too slow will cause stagnant solid fuel flow.
Solid Waste composition	The project is focused on food, paper, plastic, cardboard and moisture as the feedstock constituents. Each material has limitations in processing within a gasifier. It's unclear what the limitations are when processing shred. For pelletized fuel the plastic content shouldn't exceed 25% by weight and moisture content greater than 15%. The more variability in the feedstock will be more difficult for operation.

Table 5. Summary of waste composition from LIA study.

Waste Component		CB #1	CB #2	CB #3	CB #4	CB #5	Afghanistan Avg (Weighted)[b]
Corrugated Cardboard		9.5%	15.10%	9.3%	13.1%	16.2%	13.7%
Food Waste		15.5%	20.70%	24.5%	15.5%	24.6%	19.1%
Liquid		NR[b]	5.80%	7.4%	7.3%	6.4%	6.6%
Miscellaneous Waste		5.1%	1.10%	3.6%	1.5%	2.0%	1.6%
Mixed Paper		28.8%	13.30%	10.5%	14.4%	5.3%	13.2%
Non-Combustible	Ferrous Metal	1.2%	3.30%	5.7%	2.4%	3.5%	3.2%
	Non-Ferrous Metal	2.3%	1.80%	2.0%	1.4%	1.1%	1.6%
	Glass	1.0%	0.20%	0.2%	0.2%	0.7%	0.2%
Other Combustible		5.5%	0.50%	2.2%	2.2%	0.8%	0.5%
Plastics	#1- PET	10.6%	7.00%	5.5%	6.1%	3.2%	6.4%
	#2 - HDPE	5.0%	5.40%	4.2%	1.6%	1.6%	3.7%
	#3 - PVC	4.4%	0.70%	0.8%	0.5%	1.2%	0.7%
	#4 - LDPE/LLDPE	1.3%	2.80%	1.9%	3.1%	1.0%	2.8%
	#5 - PP	0.1%	0.20%	0.3%	0.2%	0.1%	0.2%
	#6 - PS	7.3%	2.20%	1.0%	1.2%	1.0%	1.6%
	#7 - other	0.1%	0.70%	0.4%	0.6%	0.5%	0.6%
Total Plastic (All Types)		28.8%	19.00%	14.1%	13.3%	8.6%	16.0%
Textile		1.3%	5.40%	4.1%	5.6%	3.0%	5.3%
Wood		1.0%	13.70%	16.5%	25.3%	27.0%	18.9%
Total		100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Paper/Cardboard Testing

Initial testing was completed utilizing a waste stream of 50% paper and 50% cardboard. The simplified waste stream provided an opportunity to narrow in on ideal testing parameters before switching over to more complex feeds. Tables 6 and 7 summarize the data obtained from this testing.

Table 6. Summary of test parameters and temperature results for paper/cardboard waste.

Date	Test Condition	Waste Flow Rate (lb/hr)	Producer Gas Flow Rate (cfm)	Secondary flow rate (cfm)				Maximum Temperature (°C)	Char Gasification Temperature (°C)	Difference between Max and Char (°C)
				Zone 1	Zone 2	Zone 3	Total			
2/26/2014	1	14.6	18	3	3	0	6	849	702	147
	2	14.6	18	0	3	3	6	781	738	43
3/3/2014	1	20	20	1	2	5	8	806	776	30
3/6/2014	1	20	20	0	5	3	8	774.8	761	13.8
	2	20	20	0	3	2	5	724	716	8
4/25/2014	1	21.2	18	0	3	3	6	762	734	28
	2	23	18	0	3	3	6	787	771	16
5/9/2014	1	13.33	18	0	3	3	6	779	765	14
	2	24	22	3	3	0	6	865	771	94
5/13/2014	1	14.4	18	0	3	3	6	876	751	125
	2	25.7	22	3	3	0	6	951	750	201
	3	27.69	22	4	2	0	6	932	769	163
5/16/2014	1	10	18	0	3	3	6	879	721	158
	2	13.64	18	0	3	3	6	836	742	94
	3	27	18	0	3	3	6	755	708	47
	4	19.1	18	0	3	3	6	815	802	13
5/22/2014	1	15.9	16	3	3	0	6	715	641	74
	2	18.1	20	3	3	0	6	720	680	40
	3	21.3	25*	3	3	0	6	772	690	82
6/5/2014	1	16.62	14	2.3	2.3	0	4.6	738	653	85
	2	16.16	17	2.8	2.8	0	5.6	752	684	68
	3	20.1	20	3.3	3.3	0	6.6	738	711	27
6/12/2014	1	11.78	10.5	1.7	1.7	0	3.4	869	661	208
	2	12.06	12.75	2.1	2.1	0	4.2	906	691	215
	3	14.06	15	2.5	2.5	0	5	942	731	211

Table 7. Summary of producer gas composition and energy density results for paper/cardboard waste.

Date	Test Condition	Hydrogen Content (%)	Nitrogen Content (%)	Carbon monoxide content (%)	Methane Content (%)	Carbon Dioxide Content (%)	Energy Density (BTU/ft^3)
2/26/2014	1	15.81	50.17	23.06	1.73	9.22	133.58
	2	3.06	60.25	23.91	1.36	11.42	97.83
3/3/2014	1	7.04	53.29	26.73	2.20	10.73	125.52
3/6/2014	1	10.38	53.19	24.61	1.88	9.94	124.97
	2	6.47	56.65	22.59	1.88	12.41	107.65
4/25/2014	1	13.11	49.83	23.57	2.02	11.47	130.39
	2	11.35	49.69	24.83	2.15	11.98	130.79
5/9/2014	1	5.36	58.11	23.18	1.6	11.74	103.99
	2	6.2	55.92	24.22	1.87	11.79	112.11
5/13/2014	1	7.8	57.06	22.13	1.64	11.37	107.68
	2	9.94	53.13	23.06	1.94	11.93	119.30
	3	5	59.07	19.67	1.88	14.38	94.25
5/16/2014	1	11.66	54.61	21.03	1.52	11.19	113.66
	2	5.8	58.14	22	1.81	12.24	103.32
	3	13.41	53.29	17.92	2.16	13.21	114.30
	4	7.97	63.58	12.45	1.04	14.96	71.50
5/22/2014	1	4.87	57.64	25.48	2.48	9.53	118.08
	2	7.68	57.44	22.15	2.09	10.64	111.52
	3	7.17	56.95	21.38	2.25	12.27	109.10
6/5/2014	1	7.13	59.07	19.57	2.1	12.13	101.80
	2	5.83	58.92	21.37	2.08	11.8	103.83
	3	7.35	54.95	23.89	2.59	11.22	120.79
6/12/2014	1	5.27	63.32	17.08	1.7	12.63	85.01
	2	4.25	64.34	20.84	1.54	9.04	92.85
	3	7.67	62.38	15.52	1.6	12.84	85.67

5 RESULTS AND DISCUSSION

5.1 Material Flow Characterization

5.1.1 Shredded Waste Material Flow Characterization

The following subsections summarize results of shredded waste material flow characterization. Complete data sets supporting the summation are provided in Appendix A1.

5.1.1.1 Cohesive Strength Tests

Testing revealed that the shredded MSW is cohesive and has the ability to form stable ratholes if stored in a funnel flow vessel. In addition to this “no flow” problem, funnel flow can cause erratic flow, exacerbate segregation, reduce the live capacity of the vessel, allow particle degradation (i.e. caking) in stagnant regions, and induce high loads on the structure and downstream equipment due to collapsing ratholes and eccentric flow channels.

The minimum recommended outlet diameter (DF) to avoid a rathole in a funnel flow vessel, assuming a 5-foot effective head, is six feet for shredded waste 1 and 3, and seven feed for shredded waste 4.

This data indicates that a mass flow vessel is required. In this type of vessel one would anticipate first-in-first-out flow, elimination of ratholes and the accompanying stagnant material, and minimization of segregation effects. To achieve mass flow, sizing of the outlet such that it is large enough to prevent arching is necessary. The minimum recommended outlet diameters to avoid cohesive arch in a mass flow bin are 0.3 feet for shredded waste 1 and 3, and 0.9 feet for shredded waste 4.

5.1.1.2 Particle Interlocking Tests

Each sample of shredded waste was placed in a vessel comprised of two cylinders, each equipped with two sets of crossbeams. Figure 23 is a schematic of the test vessel. The apparatus was then slowly lifted, allowing the material to discharge from the bottom.

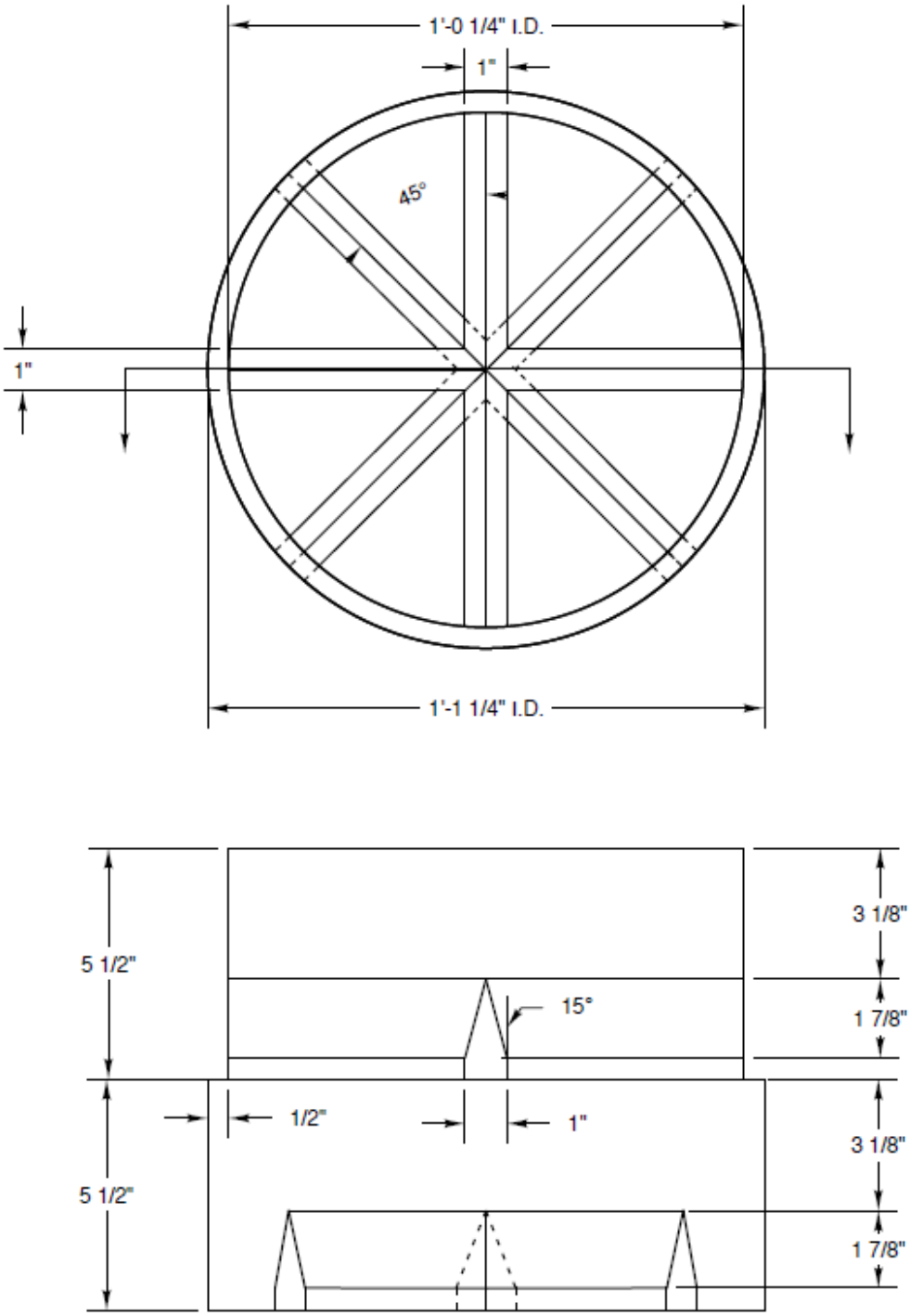


Figure 23. Particle interlock test apparatus schematic.

Each sample tested arched in the apparatus to some degree, with shredded waste 1 having the strongest blockage (entire apparatus was arched), shredded waste 4 having a more moderate blockage (three quarters of the apparatus was arched), and shredded waste 3 having the weakest blockage (one quarter of the apparatus was arched). Note that, although these results imply concerns with particle interlocking, the use of simulated gas injection cross-beams in the test

apparatus was likely a significant contributor. Converging hopper surfaces may still provide a potential for forming blockages of this type. Photographs from the tests are provided in Figures 24-29.

Figure 24. Test apparatus.

Figure 25. Arch of sample 1 (view from above).

Figure 26. Arch of sample 1 (view from below).

Figure 27. Unstable arch of sample 3 (view from above).

Figure 28. Arch of sample 4 (view from above).

Figure 29. Arch of sample 4 (view from below).

5.1.1.3 Compressibility Tests

The bulk density of most bulk solids varies with consolidating pressure. Consideration must be given to using the proper value for such calculations as vessel loads, vessel capacities, and feed density. The ranges of densities measured are given in Table 8.

Table 8. Density ranges for test materials.

Material	Measured Range, pcf
Shredded Waste 1	11.2 – 27.5
Shredded Waste 3	13.6 – 35.6
Shredded Waste 4	8.5 – 27.1

5.1.1.4 Wall Friction Tests

In addition to a properly sized outlet, the design of a mass flow vessel must consider hopper wall angles, materials of construction, and surface finish. The hopper walls must be steep enough and have sufficiently low friction to allow the material to flow along them. Wall friction angles were determined on the wall materials listed in Table 9. As an example of the test results, if a conical hopper with a one-foot diameter opening were lined or fabricated using polished refractory, the corresponding wall angles would be the maximum recommended for mass flow to occur.

Table 9. Wall friction angles for test materials.

Material	Maximum recommended mass flow wall angles[1,2,3] (from vertical), continuous flow
Shredded Waste 1	None[4]
Shredded Waste 3	4 degrees
Shredded Waste 4	None

1 – Hoppers with elongated outlets require significantly less steep angles than conical hoppers (typically 1o to 12 degrees less steep).
2 – Coupons provided by MSW Power Corp.
3 – The maximum recommended wall angle may vary, depending on outlet size. The angles specified here apply only for the outlet size stated as an example.
4 – Flow along the walls is questionable at any angle.

5.1.1.5 Permeability Test

An outlet must be sized not only to prevent arching, but also to achieve the required discharge rate. Fine powders or materials containing significant fines often exhibit a rate limitation not experienced with coarse materials that readily allow air to pass through them. In addition, the gas injection area of a process vessel must be sufficiently large in order to prevent localized fluidization of the material (which could result in channeling and other non-uniform behaviors within the vessel).

A permeability test was run to measure superficial gas velocity as a function of bulk density, as well as to calculate critical steady-state discharge rates. The gas permeability factor of a given bulk solid, K, is defined by Darcy's law as follows:

$$K = -u\gamma/(\frac{dp}{dx})$$

Where:
u = superficial gas velocity through the bed of solids
dp/dx = gas pressure gradient across the bed of bulk solids
γ = bulk density of the bed of solids

In the permeability test procedure, a constant gas pressure gradient is maintained across the bed of solids, as the bulk density is varied and the resulting superficial gas velocity is measured. The permeability test was conducted at room temperature conditions using air. From the test results, a relationship between the gas permeability factor (K) and the bulk density (γ) is obtained as follows:

$$K = K_0(\frac{\gamma}{\gamma_0})^{-a}$$

Where:
K_0 = value of K at major consolidation pressure
γ_0 = value of γ at major consolidation pressure
a = constant in gas permeation relation

Bulk solids with low permeability will have low K_0 values. The permeability test results are summarized in Table 10. In addition, the permeability test results can be used to calculate the critical steady solids discharge rates for a mass flow bin with a given outlet size and effective head. As an example of the test results, the critical steady solids discharge rate is tabulated below for mass flow cone with a one foot diameter outlet with a cylinder containing a five foot effective head of fully deaerated material.

Table 10. Permeability test results.

Material	K_0, fps	Critical steady solids flow rate, tph
Shredded Waste 1	1.82	54
Shredded Waste 3	4.00	79
Shredded Waste 4	1.18	10

5.1.2 Char Ash Material Flow Characterization

The following subsections summarize results of char ash material flow characterization. Complete data sets supporting the summation are provided in Appendix A2.

5.1.2.1 Cohesive Strength Tests

Testing was performed as previously described for shredded waste. Testing indicated that the char ash is cohesive and has the ability to form a stable rathole if stored in a funnel flow bin. In addition to this “no flow” problem, funnel flow can cause erratic flow, exacerbate segregation, reduce the live capacity of the vessel, allow particle degradation in stagnant regions, and induce high loads on the structure and downstream equipment due to collapsing ratholes and eccentric

flow channels. Fine powders such as this material will flood if the rathole collapses or fresh material is added to the vessel.

The minimum recommended outlet diameter to avoid a rathole in funnel flow is 2.1 ft, assuming a 2.5. ft effective head. The material should therefore be handled in a mass flow bin, which provides a first-in-first-out flow sequence, eliminates ratholes and the accompanying stagnant material, and minimizes segregation effects. One of the requirements for achieving mass flow is to size the outlet large enough to prevent arching. The minimum recommended outlet diameter to avoid a cohesive arch in a mass flow bin for continuous flow is 0.2 ft.

5.1.2.2 Compressibility Test

The bulk density of most bulk solids varies with consolidating pressure. Consideration must be given to using the proper value for such calculations as vessel loads, vessel capacities, and feed density. Bulk density values measured ranged from a minimum (unconsolidated) density of 22.9 pcf to 30.9 pcf over a range of consolidating pressures.

5.1.2.3 Wall Friction Tests

In addition to a properly sized outlet, the design of a mass flow vessel must consider the hopper wall angles, materials of construction, and surface finish. The hopper walls must be steep enough and have sufficiently low friction to allow the material to flow along them. It was found that within the pressures used in the test, if a mass flow vessel were lined or fabricated using polished refractory, flow of the material along the walls of the vessel would questionable at any angle.

5.1.2.4 Permeability Test

An outlet must be sized not only to prevent arching, but also to achieve the required discharge rate. Fine powders or materials containing significant fines often exhibit a rate limitation not experienced with coarse materials that readily allow air to pass through them. A permeability test was run to determine critical steady-state discharge rates. As an example of the test results, if a mass flow cone with a 0.5 ft diameter outlet were used with a cylinder containing a 2.5 ft effective head of fully deaerated material, the critical discharge rate would be approximately 0.04 tons per hour.

5.2 Experimentation

Paper/Cardboard Testing

Initial Test Results – 2/2014-3/2014

Initial testing demonstrated that, in general, the highest producer gas energy corresponds to the case where secondary air is injected just below the pyrolysis zone and the gas temperatures are highest in the region 5 to 10 inches below the gasifier inlet. This is the result of more complete combustion of the pyrolysis vapors by oxygen, generating carbon dioxide and water, which in turn produce carbon monoxide and hydrogen through the Boudouard, water gas, and water gas shift reactions. Figure 30 shows the gasifier temperature profiles at the time of the GC measurements on 02/26/2014. The positions of secondary air injection are also shown. The (3,

3, 0) secondary air configuration gave one of the highest producer gas energies in the initial test series. The first number is the quantity of secondary air, in cfm, injected through the ring of injection ports nearest the gasifier inlet (2.5 inches); the second number corresponds to the next (second) ring of injection ports; and the last figure corresponds to the third ring (7.5 inches) The temperatures at 21.25", near the exit of the gasifier, are 695°C (968K) and 733°C (1006K), and compare favorably to the equilibrium adiabatic temperature of 968K for the paper/cardboard waste stream. The producer gas energies for the 02/26/2014 test run ranged from 58% to 80% of the theoretical equilibrium adiabatic result.

For the two test runs of 03/03/2014 and 03/06/2014, air was injected into a tube placed across the width of the gasifier through two holes of diameter 0.094 inches (2.38 mm) facing downward in the direction of the gasifier exit. Secondary air was also injected through some of the sidewall injection ports. This flow configuration allowed secondary air not only to react with the waste around the periphery of the gasifier, but also in the center of the gasifier, increasing the gasification efficiency and the producer gas energy. In the test of 03/03/2014, the secondary air injection tube was located at the third ring position (7.5 inches from the gasifier inlet), while for the tests of 03/06/2014, the tube was placed at the second ring position (5.0 inches from the gasifier inlet). The producer gas flow rate and waste flow rates were 20 cfm and 10 lb/hr, respectively for the two tests. The producer gas energies ranged from 64 to 75% of the theoretical equilibrium result.

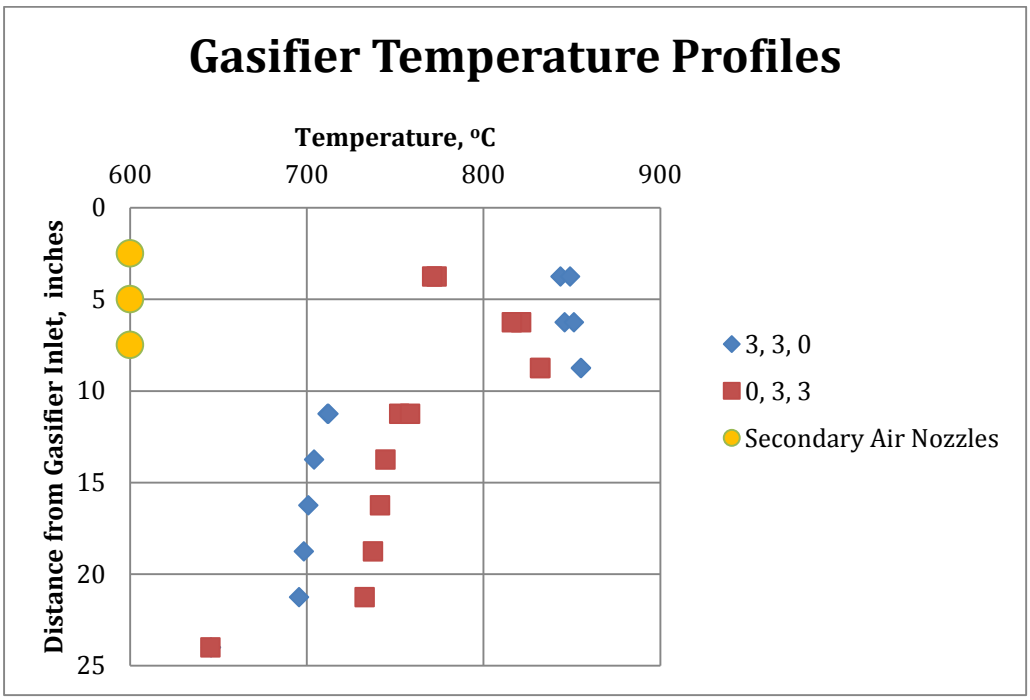


Figure 30. Gasifier temperature profiles at time of GC readings on 2/26/2014 for paper/cardboard waste.

Test Results – 4/2014-5/2014

Testing during this timeframe was aimed largely at investigating the effects of varying waste feed rates and producer gas flow rates. The producer gas energy content typically ranged from

approximately 100 to 130 BTU/ft^3. These tests often demonstrated a smaller difference in temperature between the top of the reactor and the bottom of the reactor, which lends to a temperature profile that does not promote reduction reactions. This could mean that fresh material is falling too quickly through the reactor without being converted or that there isn't enough char left in the reactor to promote the endothermic reduction reactions. The tests also show large amounts of nitrogen in the GC analysis which could be a result of excess air passing through the reactor without the equivalent amount of waste input being added to keep it in the appropriate range. Figure 31 shows the gasifier temperature profiles at the time of the GC readings on 04/25/2014. Secondary air (0, 3, 3) was injected at the 5.0" and 7.5" gasifier locations. The temperatures at the 21.25" position were 1003°K and 1041°K, a little higher than the theoretical equilibrium adiabatic temperature of 968ºK. The producer gas energies of 130 BTU/ft^3 on 04/25/2014 were 78% of the theoretical equilibrium value of 167 BTU/ft^3. For the months of April and May 2014, the measured producer energies ranged from 42% to 78% of the theoretical equilibrium adiabatic result.

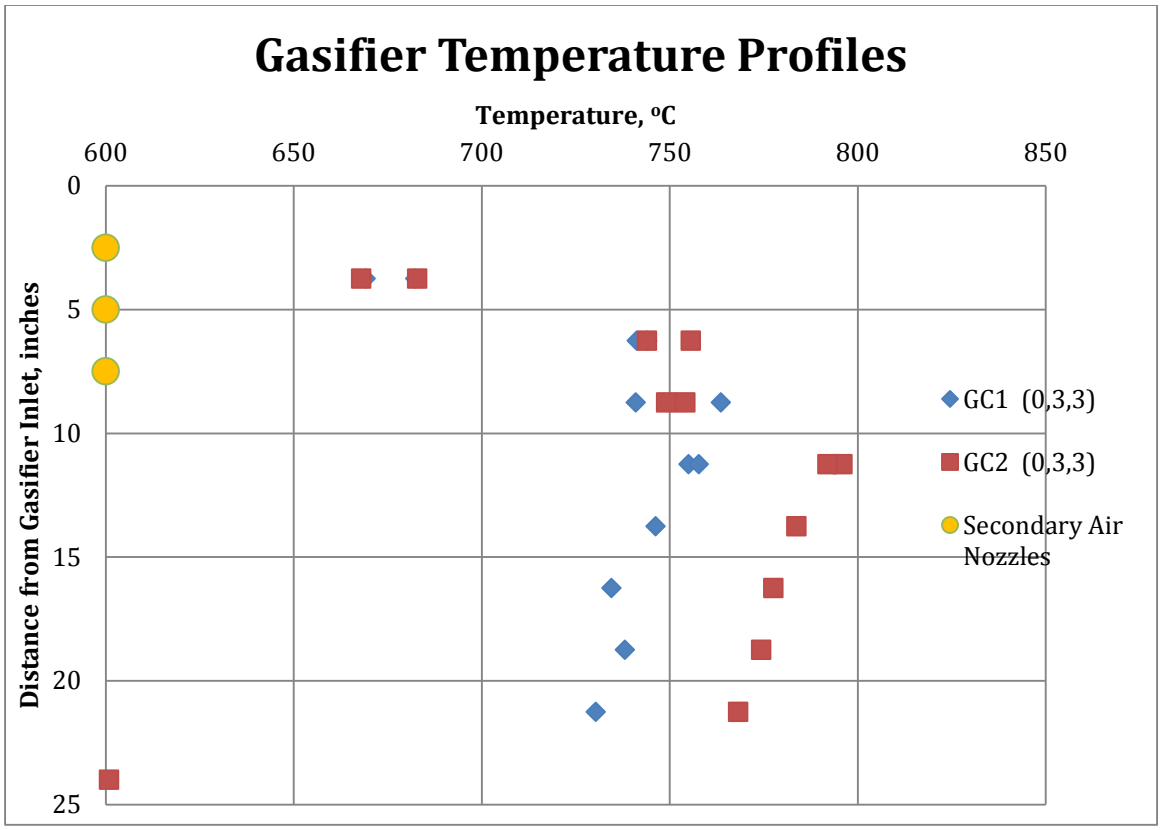


Figure 31. Gasifier temperature profiles at time of GC readings on 4/25/2014 for paper/cardboard waste.

Test Results – 6/2014

The purpose of this set of tests was to attempt to maintain consistent solid waste flow rates while varying the producer gas flowrate and keeping the ratio of primary to secondary air consistent. This set of tests was also the last before moving towards mixed waste streams. The first set of

tests demonstrated higher temperatures but lower producer gas flow energy contents compared to the earlier test runs. The second set resulted in a much more ideal temperature profile but the producer gas flow energy content was low largely due to a large amount of nitrogen. As mentioned previously, it appears that a large amount of air could potentially be passing through the reactor without enough waste being reacted to keep the nitrogen content lower. Figure 32 shows the gasifier temperature profiles at the time of the GC readings for 06/06/2014. The highest producer gas energy corresponded to a producer gas flow rate of 20 cfm and an adiabatic gas temperature of 980K (707°C), close to the theoretical value of 968K. The producer gas energies ranged from 52% to 72% of the theoretical equilibrium adiabatic result.

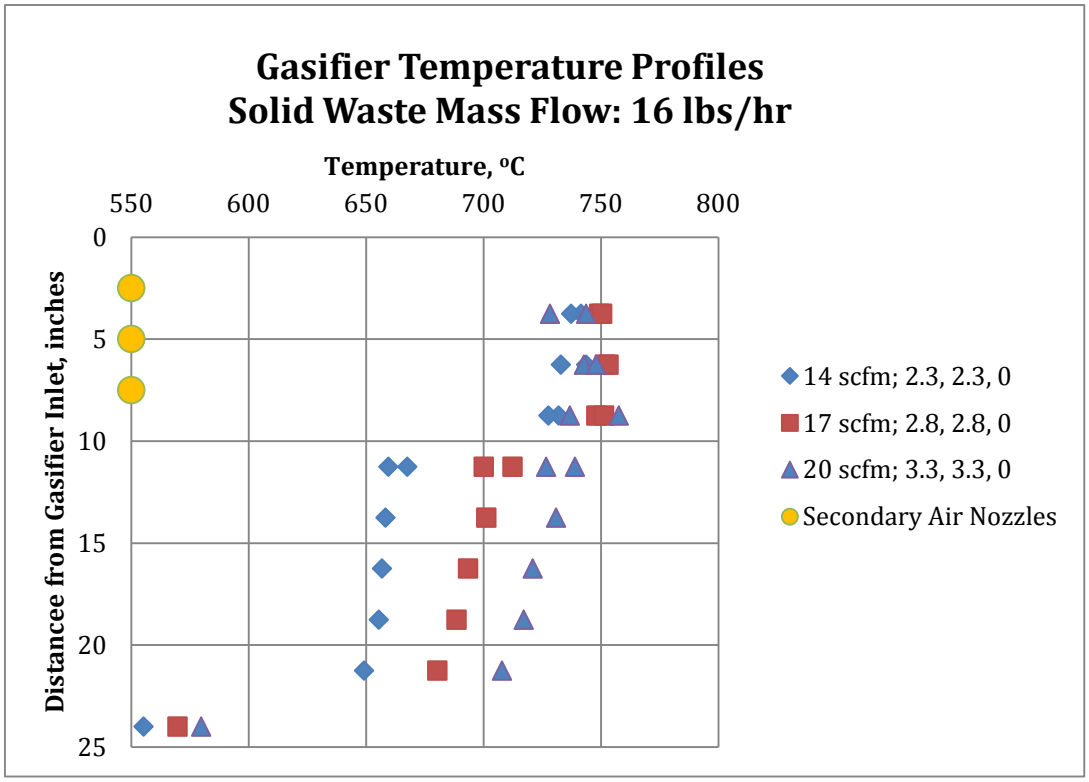


Figure 32. Gasifier temperature profiles at time of GC readings on 6/25/2014 for paper/cardboard waste.

The diverging rectangular configuration that opens in the direction of the solids flow resulted in bulk solids mass flow. This configuration enabled uniform velocity of the moving solids across any given cross-section without any regions of stagnant flow. Thus the first objective of the test plan was met. Analysis of the test results in Tables 11 and 12 shows there is no preferred secondary air configuration that optimizes the producer gas energy. For example, the following secondary air configurations gave producer gas energies in the range 100 to 135 BTU/ft^3:

- Nine air injection configurations with air injection in the two rings closest to the gasifier inlet (2.5 and 5 inches).
- Nine configurations with air injection in the lower two rings (5 and 7.5 inches).
- One configuration with air injection in all three rings (2.5, 5 and 7.5 inches).

Table 11. Summary of test parameters and temperature results for mixed waste #1.

Date	Test Condition	Waste Flow Rate (lb/hr)	Producer Gas Flow Rate (cfm)	Secondary flow rate (cfm)					Maximum Temperature (°C)	Char Gasification Temperature (°C)	Difference between Max and Char (°C)
				Zone 1	Zone 2	Zone 3	Zone 4	Total			
8/28/2014	1	11.7	12.75	2.1	2.1	0	0	4.2	817	616	201
	2	13.1	15	2.5	2.5	0	0	5	868	675	193
	3	13.5	17.25	2.9	2.9	0	0	5.8	810	634	176
9/5/2014	1	13.1	12.75	2.1	2.1	0	0	4.2	889	682	207
	2	13.65	15	2.5	2.5	0	0	5	933	737	196
	3	15.24	17.25	2.9	2.9	0	0	5.8	904	732	172

Table 12. Summary of producer gas composition results for mixed waste mixture #1.

Date	Test Condition	Hydrogen Content (%)	Nitrogen Content (%)	Carbon monoxide	Methane Content (%)	Carbon Dioxide Content (%)	Energy Density (BTU/ft^3)
8/28/2014	1	10.36	62.03	13.6	1.38	12.63	84.88
	2	13.87	60.23	12.95	1.28	11.67	91.53
	3	4.51	64.19	16.05	2.05	13.21	82.80
9/5/2014	1	13	57.4	15.48	1.49	12.63	99.20
	2	13.16	59.9	14.38	0.9	11.67	90.71
	3	7.38	62.11	16.06	1.39	13.07	84.70

Mixed Waste Testing

The results of these trials are summarized in Tables 13 and 14.

Mixed Waste Mixture #2

Testing proceeded with a more relevant mixture containing higher moisture content. The feed waste composition for this round of trials is given below:

- 22 wt% cardboard.
- 22 wt% paper.
- 33 wt% food.
- 13 wt% plastic.
- 10 wt% added moisture.

Table 13. Summary of test parameters and temperature results for mixed waste mixture #2.

Date	Test Condition	Waste Flow Rate (lb/hr)	Producer Gas Flow Rate (cfm)	Secondary flow rate (cfm)					Maximum Temperature (°C)	Char Gasification Temperature (°C)	Difference between Max and Char (°C)
				Zone 1	Zone 2	Zone 3	Zone 4	Total			
9/10/2014	1	13.67	20.5	2.1	2.1	0	0	4.2	777	579	198
	2	14.26	27	2.1	2.1	0	0	4.2	835	642	193
	3	16.4	30.5	3	3	0	0	6	851	686	165
9/17/2014	1	13.26	15	1.5	1.5	0	0	3	755	554	201
	2	15.62	18	2	2	0	0	4	735	564	171
9/23/2014	1	11.7	15	1.5	1.5	0	0	3	771	566	205
	2	12.8	18	2	2	0	0	4	819	632	187
9/26/2014	1	11.54	15	0	1.5	1.5	0	3	777	585	192
	2	14.4	15	0	2	2.5	0	4.5	754	567	187
	3	16.56	18	0	2	2.5	0	4.5	757	588	169
10/1/2014	1	15.05	18	0	2	2	0	4	755	551	204
	2	14.83	26	0	2	2	0	4	712	493	219
	3	11.78	26	0	2	2	0	4	781	537	244
10/27/2014	1	20.63	25	0	4	4	0	8	792	661	131
	2	23.91	28	0	4	4	0	8	827	694	133
	3	28.03	30	0	4	4	0	8	804	669	135
10/29/2014	1	20.26	18	0	3	3	0	6	770	615	155
	2	17.66	21	3	3	0	0	6	818	655	163
	3	16.28	21	1	4	1	0	6	874	722	152
10/31/2014	1	15.5	20	1	2	3	0	6	752	591	161
	2	17.71	20	2	4	0	0	6	842	646	196
	3	14.11	20	0	4	2	0	6	926	761	165
11/4/2014	1	17.06	16	0	3	3	0	6	728	585	143
	2	15.13	18	0	3	3	0	6	751	613	138
	3	17.91	20	0	3	3	0	6	854	702	152
11/7/2014	1	17	18	0	2	3.8	1.4	7.2	801	652	149
	2	17	26	0	4.5	1	0	5.5	818	662	156
	3	17	29	0	0	0	0	0	761	568	193
11/10/2014	1	21.11	18	1	2	3	0	6	828	671	157
	2	21.53	22	2	4	0	0	6	864	697	167
	3	15.22	26	0	4	2	0	6	843	685	158
11/14/2014	1	15.94	18	0	2	4	0	6	735	566	169
	2	16.21	18	1	3	2	0	6	832	665	167
	3	17	18	3	2	1	0	6	867	733	134
11/18/2014	1	11.99	18	1	2	2	0	5	812	623	189
	2	12.55	16	1	2	2	0	5	826	644	182
	3	13.75	14	1	2	2	0	5	784	621	163

9/10/2014 Test

The moisture weight is the amount of water added to the mixture. According to the Hazen ultimate and proximate analyses, the water content of the mixture was 15.95%, indicating that the water content of the food in the mixture was 5.95%. An equilibrium analysis of the Mixture #2 composition was done and the results are shown in Figures 33 and 34. In Figure 33, the producer gas energy is plotted against the gasification temperature in the lower part of the reactor. The theoretical equilibrium adiabatic temperature is 1002K (729°C); this is the temperature that the reduction reactions take place in the reactor, occurring without any heat transfer between the gas and the reactor surface. The test results show that the producer gas energy is between 70 to 90 BTU/ft^3, which is much lower than the theoretical equilibrium value of 175 BTU/ft^3.

Figure 34 shows the producer gas energy as a function of the producer gas flow rate. The low energies seem to be a result of the high producer gas flow rates, where the high nitrogen content (60-65%) dilutes the producer gas and reduces the producer gas energy. Figure 35 shows the gasifier temperature profiles at the time of the GC reading on 09/10/2014.

The results for the remainder of the tests with the mixed waste mixture #2, were generally similar to the results of the tests of 09/10/2014. The producer gas energies for the mixed waste mixtures were consistently lower than the energies for the paper/cardboard waste.

Table 14. Summary of producer gas composition results for mixed waste mixture #2.

Date	Test Condition	Hydrogen Content (%)	Nitrogen Content (%)	monoxide content (%)	Methane Content (%)	Carbon Dioxide Content (%)	Energy Density (BTU/ft^3)
9/10/2014	1	10.65	63.65	12.9	0.81	11.99	78.22
	2	9.8	65.01	10.81	1.06	13.33	71.44
	3	11.83	60.69	14.41	1.27	11.79	90.53
9/17/2014	1	9.95	63.63	11.73	1.41	13.28	78.01
	2	7.02	66.49	11.13	1.54	13.83	69.20
9/23/2014	1	7.51	66.71	11.67	1.13	12.97	68.55
	2	7.35	66.5	12.52	1.27	12.37	72.12
9/26/2014	1	8.2	63.56	16.57	0.89	10.78	84.03
	2	6.16	65.13	15.93	1.22	11.57	79.37
	3	6	65.94	14.73	0.78	12.55	71.05
10/1/2014	1	8.78	64.17	13.02	1	13.03	75.20
	2	7.09	62.32	16.2	2.32	12.07	92.84
	3	7.3	63.93	16.89	1.79	10.09	90.80
10/27/2014	1	8.24	59.86	19.69	1.24	10.96	97.38
	2	6.93	61.89	18.24	1.3	11.64	89.66
	3	10.45	58.88	17.32	1.6	11.74	99.12
10/29/2014	1	20.34	52.01	14.34	1.51	11.81	115.90
	2	3.61	63.83	16.86	1.86	13.84	81.20
	3	8.91	60.27	15.88	1.31	13.62	87.60
10/31/2014	1	14.41	54.2	18.24	1.67	11.49	113.61
	2	11.67	57.9	16.06	1.67	12.7	99.05
	3	10	59.31	18.41	0.94	11.33	95.36
11/4/2014	1	9.26	58.66	18.77	1.7	11.61	101.43
	2	11.9	57.68	19.02	1.33	10.07	106.11
	3	3.96	62.69	19.77	1.42	12.17	87.51
11/7/2014	1	8.22	60.01	20.28	1.21	10.28	98.95
	2	7.79	61.52	16.78	1.73	12.18	91.25
	3	13.07	59.17	16.23	1.01	10.52	97.42
11/10/2014	1	6.07	61.28	19.67	1.06	11.93	89.71
	2	9.48	60.27	17.38	1.31	11.57	93.99
	3	5.96	59.9	20.12	1.77	12.25	97.34
11/14/2014	1	6.08	58.44	22.24	2.09	11.15	107.41
	2	6.74	62.81	16.93	1.06	12.46	82.73
	3	9.77	60.26	15.71	1.56	12.7	91.70
11/18/2014	1	7.09	60.32	19.62	1.32	11.64	94.73
	2	11.56	58.75	16.97	1.31	11.41	98.39
	3	12.33	59.63	15.33	1.2	11.51	94.23

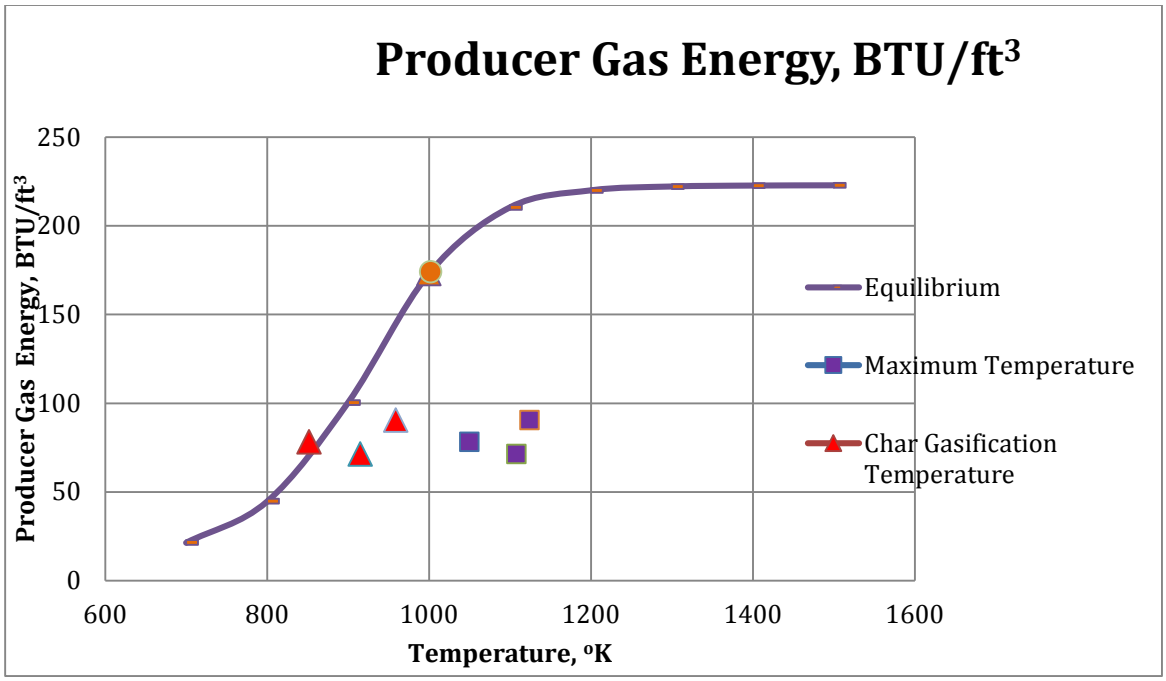


Figure 33. Producer gas energy vs char reduction temperature for mixed waste mixture #2.

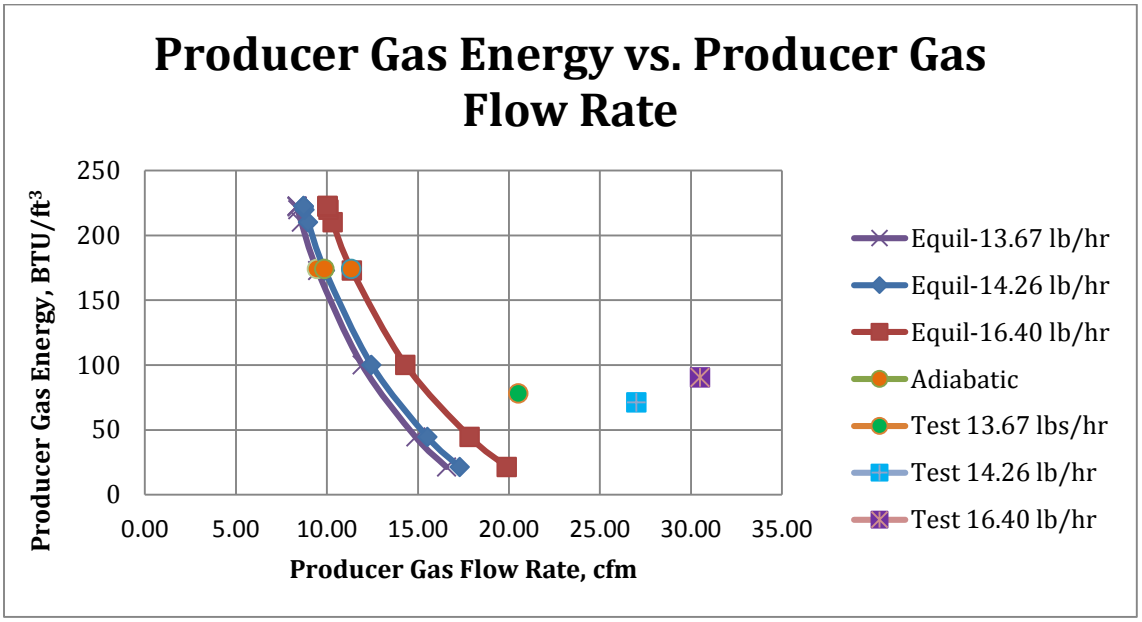


Figure 34. Producer gas vs flow rate for mixed waste mixture #2**.**

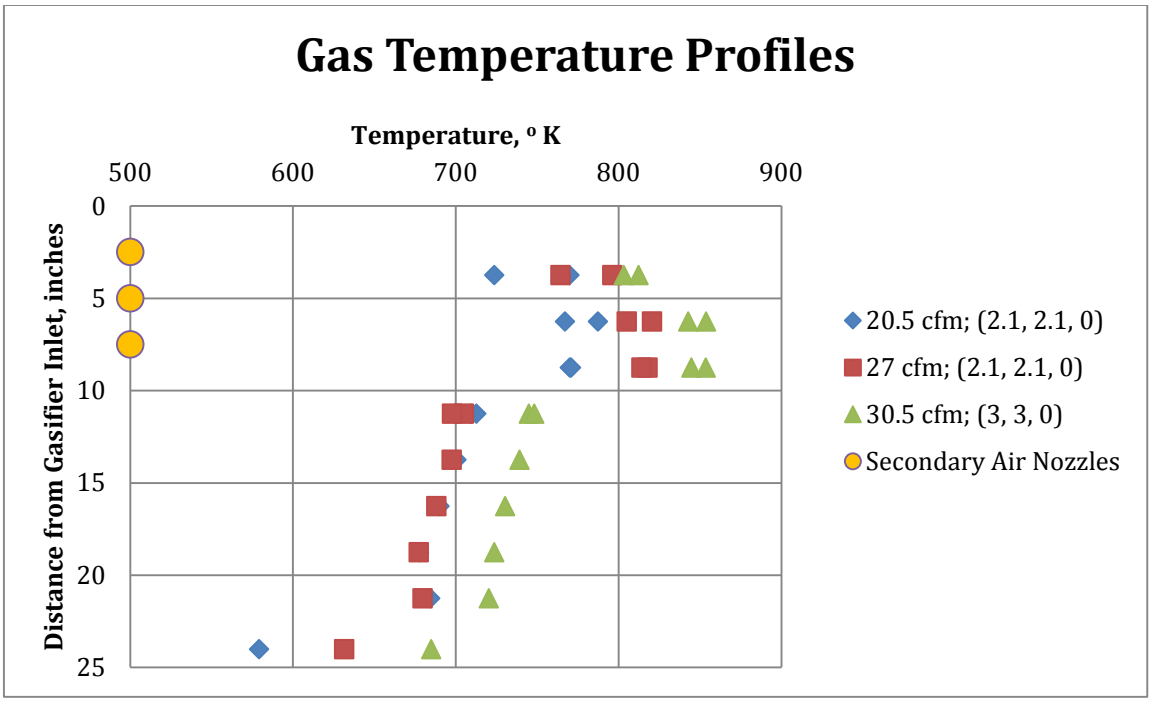


Figure 35. Gasifier temperature profiles at time of GC readings on 9/10/2014 for mixed waste mixture #2

5.3 Analyze and Evaluate Results

Figure 36 and Table 15 summarize test data for the energy contained in the producer gas (syngas) for a diverging downdraft gasifier in which the area of the gasifier increases in the direction of the flow of the shredded waste feed stock. In the first series of tests, the shredded waste feed stock consisted of paper and cardboard, while the shredded feed stock in the second series of tests consisted of cardboard, paper, plastic, water, and food. Producer gas energy was estimated using the feed stock composition as an input to an equilibrium analysis of the gasification process at adiabatic conditions. In the gasification zone, three reactions dominate; namely, Boudouard, water gas, and water gas shift reactions. The equilibrium producer gas energy for the shredded mixed waste at adiabatic conditions was 174 BTU/ft^3 compared to 166 BTU/ft^3 for the shredded paper/cardboard, slightly higher because of the energy content of the plastics. However, the test data showed consistently higher producer gas energies for the shredded paper/cardboard waste. Seventy percent (70%) for the shredded paper cardboard tests had a producer gas energy > 100 BTU/ft^3 compared to 12 percent for the shredded mixed waste; and 88% of the shredded mixed waste tests had a producer gas energy < 100 BTU/ft^3 compared to 30% for the shredded paper/cardboard tests.

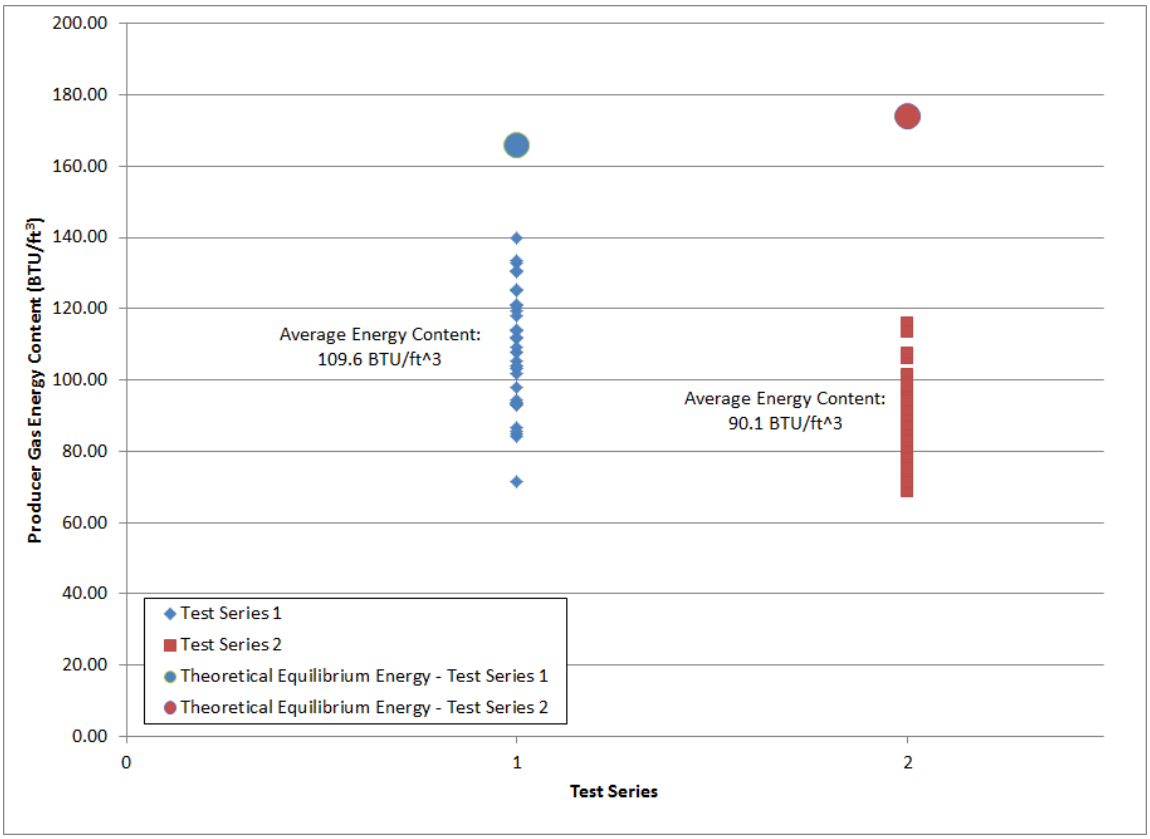


Figure 36. Summary of test data for gasification trials using shredded paper/cardboard and mixed waste mixtures.

Table 15. Summary of producer gas energy results.

Producer Gas Energy, BTU/ft^3	**Test Series 1 Shredded Paper/Cardboard Number in Range (% Total)**	**Test Series 2 Shredded Mixed Waste Number in Range (% Total)**
Total Test Runs	33	42
>100	23 (69.7)	5 (11.9)
100-110	7	3
110-120	6	2
120-130	4	-
130-140	6	-
<100	10 (30.3)	37 (88.1)
90-100	6	20
80-90	4	10
70-80	-	7
Equilibrium Adiabatic	167 BTU/ft3	174 BTU/ft^3

Secondary air is required to combust the pyrolysis gas to form CO_2 and H_2O, which then reacts with char in the gasification zone (below the pyrolysis zone) to form CO and H_2, the primary energy constituents of the producer gas. In the diverging downdraft gasifier, the secondary air is injected in the pyrolysis zone normal to the direction of the solid waste mass flow. For high conversion efficiency, the secondary air must penetrate to the center of the gasifier, reacting with

as much of the waste in the pyrolysis zone as possible to produce an active char in the gasification zone. The test results could be attributed to the higher resistance (lower permeability) of the shredded mixed waste to secondary air flow in the pyrolysis zone as compared to the paper/cardboard shredded waste. For example, at comparable producer gas and shredded waste flow rates (20 cfm, 18 lbs/hr), the pressure drop across the reactor (top inlet – bottom outlet) for mixed shredded waste is 46.5 WC versus 6.4 WC for paper/cardboard shredded waste, a factor of 7.3 times the differential pressure, indicating higher resistance and lower permeability for the mixed shredded waste. The calculated flow resistances for the paper/cardboard and mixed waste are 366 sec/m and 2672 sec/m, respectively; the permeabilities are $2.73*10^{-3}$ m/sec and $3.74*10^{-4}$ m/sec, respectively.

SolidWorks flow simulation analyses showed for the range of flow resistances used in the test program the secondary air never penetrated to the center of the gasifier. The secondary air penetrated further into the center of the gasifier for the shredded paper/cardboard waste compared to the mixed waste.

To achieve high conversion efficiency, secondary air flow should react with the shredded waste throughout the cross section of the gasifier and not only near the gasifier walls. This is suggested by the two shredded paper/cardboard tests in which secondary air was not only injected around the periphery of the gasifier, but in the center of the gasifier through a single injection tube placed across the width of the gasifier. Another way to achieve high conversion efficiency is to insert crossbeams in and across the pyrolysis section of the diverging reactor that are tapered in the flow direction. The crossbeams would contain flow annuli for effective injection of the secondary air in a high pressure drop environment without causing the bulk solids to be hung up in the reactor. Construction materials for the tapered crossbeams should not be an issue because of the relatively low temperatures (about 400°F) in the pyrolysis region. Additionally, locating the annulus at the top of the reactor and at the lower temperatures decreases the concern of sagging due to the weight of material above it at a high temperature. The grate opening should be large enough to avoid blockages due to the formation of stable, cohesive arches, as well as "mechanical arches" caused by interlocking of larger particles over the grate opening.

The diverging tapered gasifier design resulted in bulk solids mass flow without any regions of stagnant flow in the gasifier due to bridging or arching. This configuration enabled uniform velocity of the moving solids across any given cross-section without any regions of stagnant flow. The data also showed that there is no preferred secondary air configuration that optimized the producer gas energy, just as long as secondary air injection is within the pyrolysis zone. This results in more complete combustion of the pyrolysis vapors by oxygen, generating carbon dioxide and water, which in turn produces carbon monoxide and hydrogen through the Boudouard, water gas and water gas shift reactions.

6 CONCLUSIONS AND IMPLICATIONS FOR FUTURE RESEARCH/IMPLEMENTATION

6.1 Scale-Up of Shredded Waste Gasifier

Table 16 shows a comparison of the shredded waste and pelletized waste gasifier configurations. The first column shows the various properties of the shredded waste and inverted rectangular gasifier configuration for the laboratory tests performed during this effort. The second column shows the configuration of the GEM gasifier developed by MSW Power and used at Edwards AFB and the Plymouth County Correctional Facility in Plymouth MA with waste pellets. Many of the design parameters are based on this system. The third column is the inverted rectangular configuration scaled-up to 200 lb/hr of shredded waste, the design point for the SERDP shredded waste-to-energy system.

The major differences between the GEM and the shredded waste gasifier configurations are the following:

- Density of the waste at the top of the gasifier.
- Area of the GEM decreases towards the bottom of the gasifier while the area of the shredded waste gasifier increases.

With regards to the position, number and diameter of the secondary air nozzles, it is recommended to use three secondary air rings and place the nozzles in the same relative configuration as in smaller lab gasifier. The first ring should be about 5.4 inches from the top of the gasifier, the second ring about 10.9 inches, and the third ring about 16.4 inches. On each ring, three nozzles should be placed on each of the long sides and one nozzle on each of the short sides. In looking over the test runs, the maximum secondary air injection was 9 scfm with two rings, or about 40% of the total syngas. For 1/8” diameter nozzles, the velocity through each nozzle is 55 ft/sec. For the large gasifier, the secondary air through the wall nozzles should be about 50% of the total, or 65 scfm. For a nozzle diameter of 1/8” inch, the same number of nozzles per ring and for secondary air injection through two rings, the nozzle velocity is about 800 ft/sec, or about 14.5 times the secondary velocity of the smaller gasifier. This should promote better penetration of the secondary air into the center of the gasifier.

For a high conversion efficiency, the secondary air should react with the shredded waste throughout the cross-section of the gasifier, and not only near the gasifier walls. One way to accomplish this is to insert crossbeams in and across the pyrolysis section of the diverging reactor that are tapered in the flow direction. The cross beams should be placed just above the first ring of nozzles, or about 4.5 inches from the top of the gasifier. The flow annuli on the cross beams should be placed within a region of about half the length of each cross beam, which is approximately the penetration depth of the secondary air injected through the walls of the gasifier. For the scaled up configuration, the annuli should be placed within 3.5 inches of the center of the 14” cross beam and within 5.25 inches of the center of the 21” cross beam. It is suggested that the system use 4 annuli in each cross beam with a total flow capacity of about 60-70 cfm. Rather than having a high velocity for penetration, as with the side nozzles, the annuli

should be larger than the side nozzles for better flow distribution, approximately 0.5 inches in diameter, with a flow capacity of about 4 scfm per nozzle.

Table 16. Shredded waste and pelletized waste gasifier configurations.

	Inverted Rectangle Lab Cofiguration	GEM 3 tons/day Pellets	Inverted Rectangle Scaled-Up 3 tons/day
Shredded Mass Waste Flow Rate, lb/hr	16.7	200	200
Shredded Waste Volumetric Flow Rate, ft^3/hr	1.285	6.250	15.385
Syngas Flow Rate, ft^3/min	14.2	130	130
Taper angle, degrees	5		5
Waste converted to char/ash,	0.95	0.95	0.95
*Waste density, top of gasifier, lb/ft^3	13	32	13
*Waste density, bottom of gasifier, lb/ft^3	26.5	18	26.5
Diameter end circle/diameter cone*, inches			
Length center section (constant)*, 10 inches	-		
Diameter of Opening, inches		19.25	
Length one side of rectangle*, inches	6		21.00
Length second side of rectangle*, inches	4		14.00
Area, top of gasifier, ft^2	0.167	2.0211	2.04
Area, bottom of gasifier, ft^2	0.581		4.83
Height of gasifier, in	24	49.75(32 + 17.75)	52
Volume of gasifier, ft^3	0.707	6.75	14.47
Waste residence time*, min	33.051	80	56.477
Superficial gas velocity, ft/sec	1.42	1.07	1.06
Position of Secondary Air Nozzles			
Ring 1, inches from top of gasifier	2.50	8.8	5.4
Ring 2, inches from top of gasifier	5.00	14.30	10.92
Ring 3, inches from top of gasifier	7.50	19.80	16.42
Relative to GEM			
Waste mass flow rate	0.0835	1.00	1.00
Waste volumetric flow rate	0.206	1.00	2.462
Gasifier Volume	0.105	1.00	2.143
Syngas volumetric flow rate	0.109	1.00	1.00
Residence time	0.413	1.00	0.706
Superficial velocity	1.325	1.00	0.990

The final system design will include the following operations upstream from the gasifier (these operations collectively represent the solid waste preprocessor and will be housed in a single ISO shipping container):

- Shredder
  - To reduce raw waste into a consistent particle size. A hopper sits on top of the shredder to store waste as it is charged into the system by the Front End Loader.
- Wet shred conveyance
  - To convey wet shredded material for downstream processing.
- Fluidized bed dryer

        - Removes moisture from the shred to hit a 10-15% by weight target. Heat for the drying operation comes from the engine exhaust heat exchanger and can support up to 70% moisture content at 300 lbs/hr.
        - Moisture monitoring measures the input and output moisture content and controls the amount of heat required for the dryer and the retention time of the material in the dryer.
    - Dryer exhaust cyclone
        - Removes any waste particles that were entrained in the dryer exhaust gas. A drum collects the particles and will be dumped by an operator back into the shredder (using the Front End Loader).
    - Shred storage
        - Stores dry shred for processing in the gasifier.
    - Shred conveyance
        - Feeds material into the gasifier.
    - Controls
        - All controls are distributed throughout each container due to size constraints. A main PLC is located in the generator container. Each container has a power and I/O cabinet that operates the equipment in each container. All intelligence is communicated by the main PLC through Ethernet to each power and control box.
    - Supporting electrical components
        - The SWP system has a load panel for internal lights, outlets and other general 120V requirements.
        - Junction boxes are commonly used to reduce the amount of cable harnesses in the container.
        - Wire trough is used to support large bundles of wires throughout the container.
    - ESTOP
        - Each container has a pair of ESTOP buttons on the exterior for an operator to shut down the operation if an adverse condition occurs.
    - Exhaust Fan
        - The SWP has an exhaust fan to keep the internal container environment clean and cool. The fan does 20 container changes an hour while filtering the discharge air for containments and odor.

6.2 System Renderings

Based on the results of this SERDP effort, a containerized gasification system capable of processing shredded mixed waste streams has been conceived. The system will feature a preprocessing system as described in Section 6.1. This preprocessing system represents a significant departure from one utilized for a pellet-fed gasification system. The anticipated advantages of this new configuration are a reduced system weight and a reduced system cost.

Figures 37-39 provide CAD renderings of the preprocessing system, and Figures 40 and 41 provide external views of the preprocessing system in a containerized configuration.

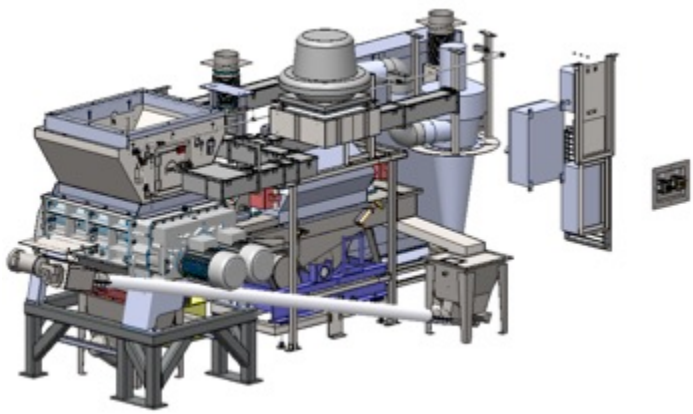


Figure 37. Front view of internal components for scaled up shredded waste gasifier system.

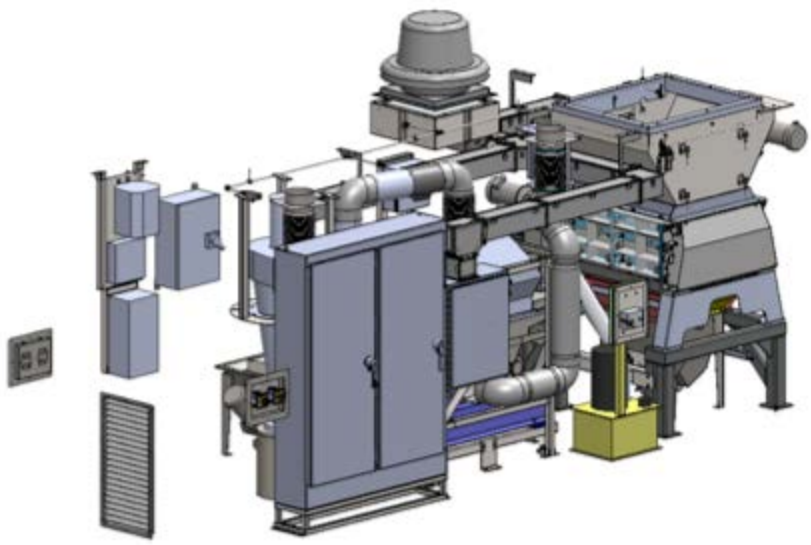


Figure 38. Back view of internal components for scaled up shredded waste gasifier system.

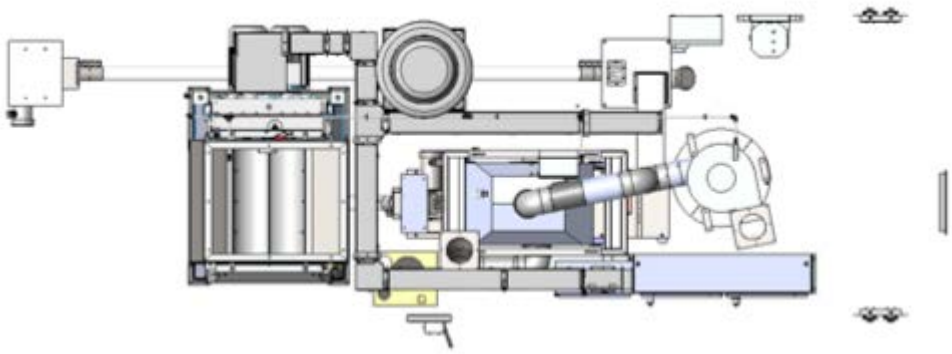


Figure 39. Top view of internal components for scaled up shredded waste gasifier system.

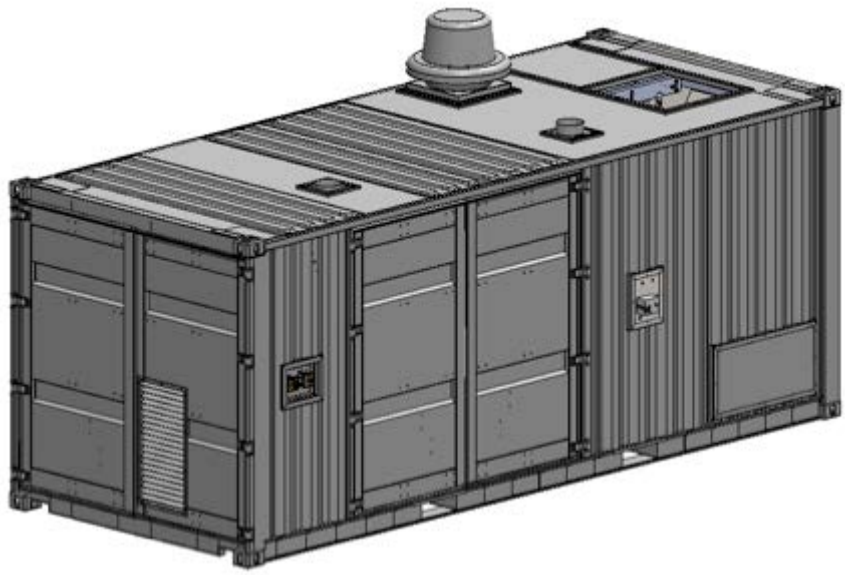


Figure 40. Front view of shredded waste gasifier container.

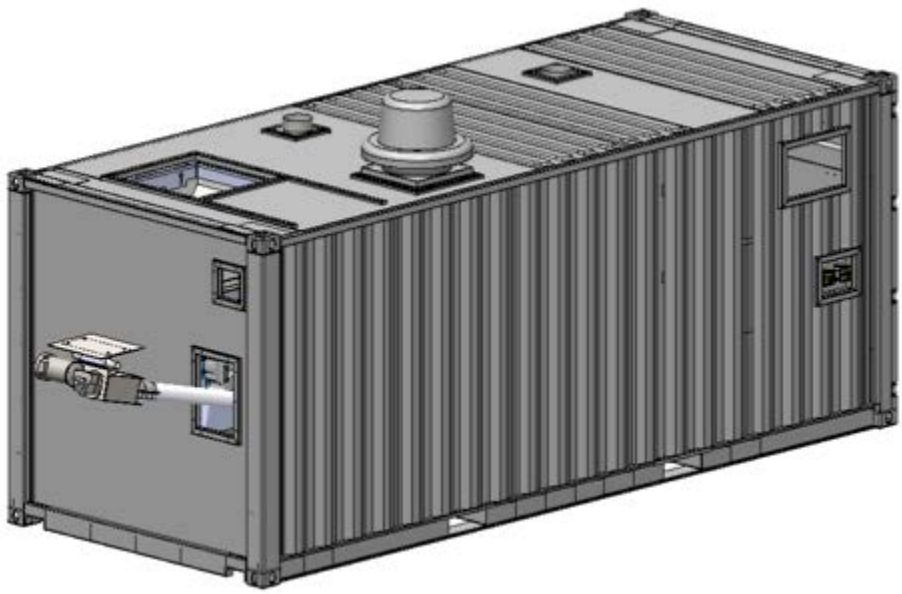


Figure 41. Back view of shredded waste gasifier container.

Conveyance of the shredded waste from the preprocessing system to the shredded waste gasification system will be controlled by an automated logic system. Feed rates will be slaved to gasifier outputs and ultimately to system load. Figures 42 and 43 provide renderings of the gasification system. The gasification system will include:

- Shredded Waste Gasifier
  - Based on the outputs of this SERDP project, the gasifier will be sized to handle 2-3 tons of shredded waste per day. The gasifier will include the reactor with secondary air manifold and the reactor base.

- Heat Exchanger
  - A shell-and-tube heat exchanged will be required to drop the producer gas temperature down to a suitable level such that lower cost materials of construction can be used for downstream processing equipment.
- Filtration
  - The producer gas will be cleaned to remove particulate matter and any residual tar prior to passing to the genset.
- Controls
  - All controls are distributed throughout each container due to size constraints. A main PLC is located in the generator container. Each container has a power and I/O cabinet that operates the equipment in each container.
- Supporting electrical components
  - The system has a load panel for internal lights, outlets and other general 120V requirements.
  - Junction boxes are commonly used to reduce the amount of cable harnesses in the container.
- ESTOP
  - Each container has a pair of ESTOP buttons on the exterior for an operator to shut down the operation if an adverse condition occurs.
- Exhaust Fan
  - The gasification system has an exhaust fan to keep the internal container environment clean and cool. The fan does 20 container changes an hour while filtering the discharge air for containments and odor.

Downstream of the gasification system container will be a third container housing a modified diesel genset. The container will house:

- Modified Diesel Genset
  - Modification of the genset will be primarily focused on alteration of the engine side such that co-firing of diesel/JP fuel variants with the producer gas is accommodated.
- Liquid Fuel Storage
  - A storage tank capable of holding a sufficient quantity of storage will be included.
- Controls, Electrical Components, and ESTOP as described for the two other containers
- Any Secondary Best Available Control Technology
  - If use scenarios and waste inputs require secondary air quality measures, these will be contained in this container. Selection of the best available control technology will be on a case-by-case basis.
- Maintenance Supplies
  - Storage for typical maintenance supplies required for preventative and as-needed maintenance will be contained within this container.

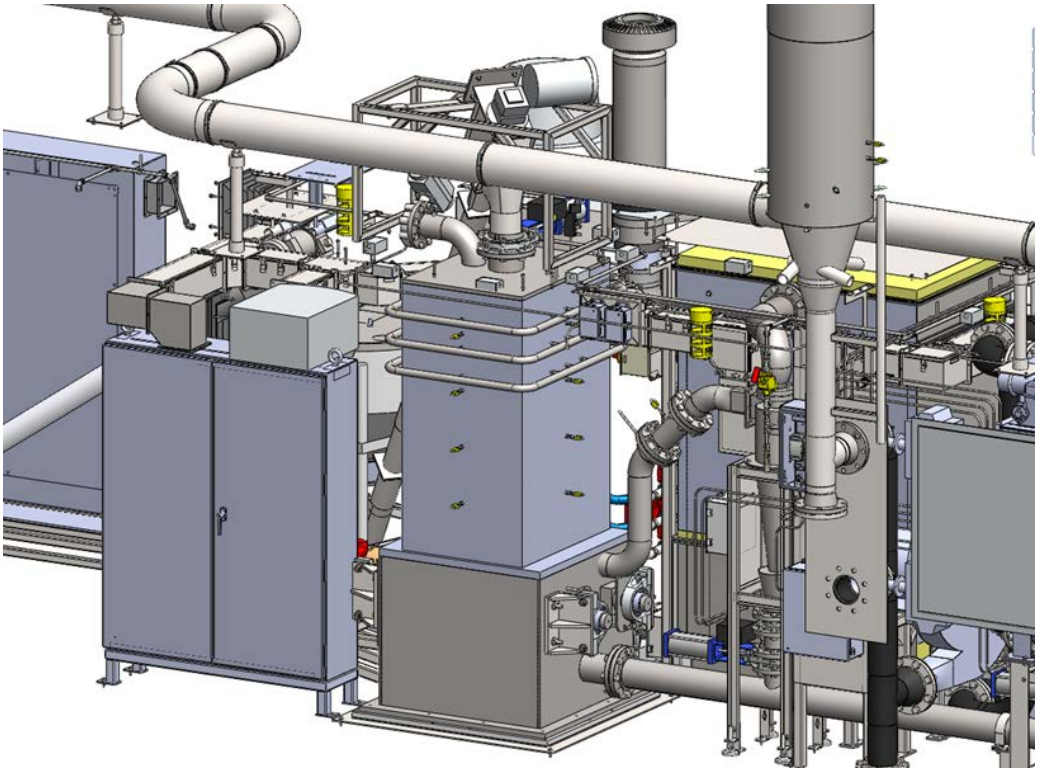


Figure 42. View of the gasification system featuring the shredded waste reactor.

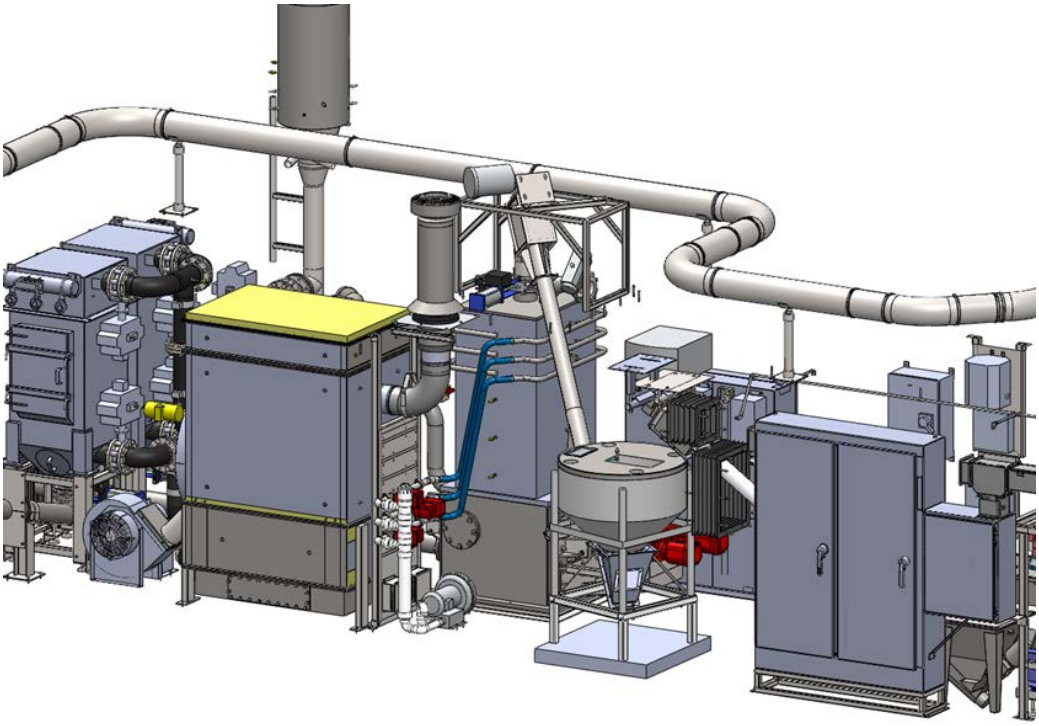


Figure 43. Alternate view of the gasification system.

Figure 44-56 provide full system views.

Figure 44. Integrated containerized waste to energy conversion system featuring shredded waste gasifier – side views.

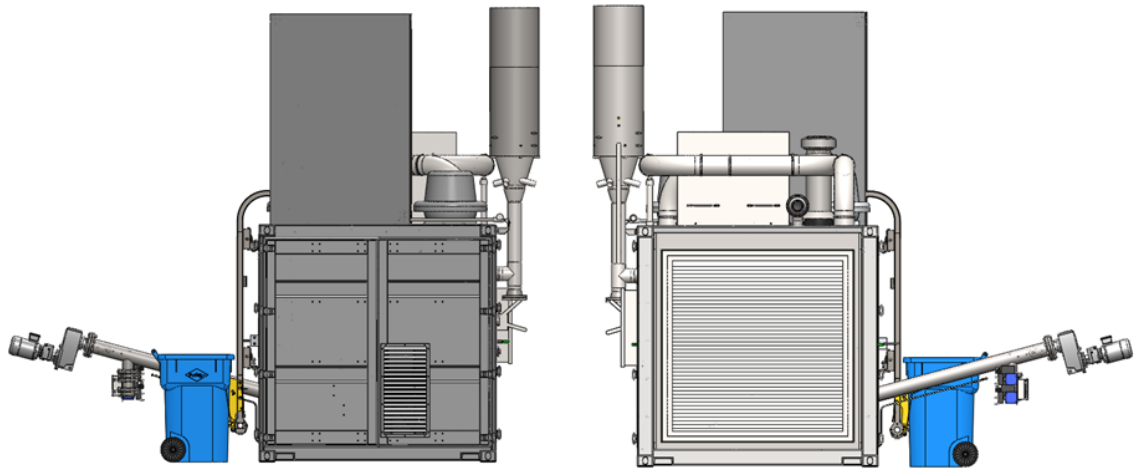


Figure 45. Integrated containerized waste to energy conversion system featuring shredded waste gasifier – end views.

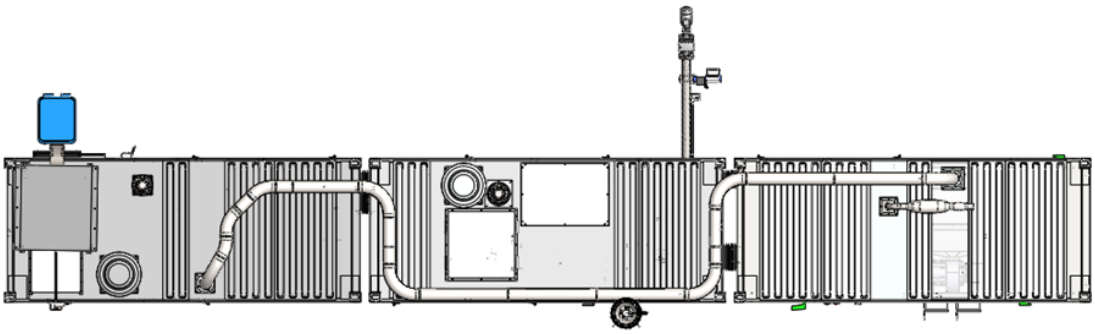


Figure 46. Integrated containerized waste to energy conversion system featuring shredded waste gasifier – alternate side view.

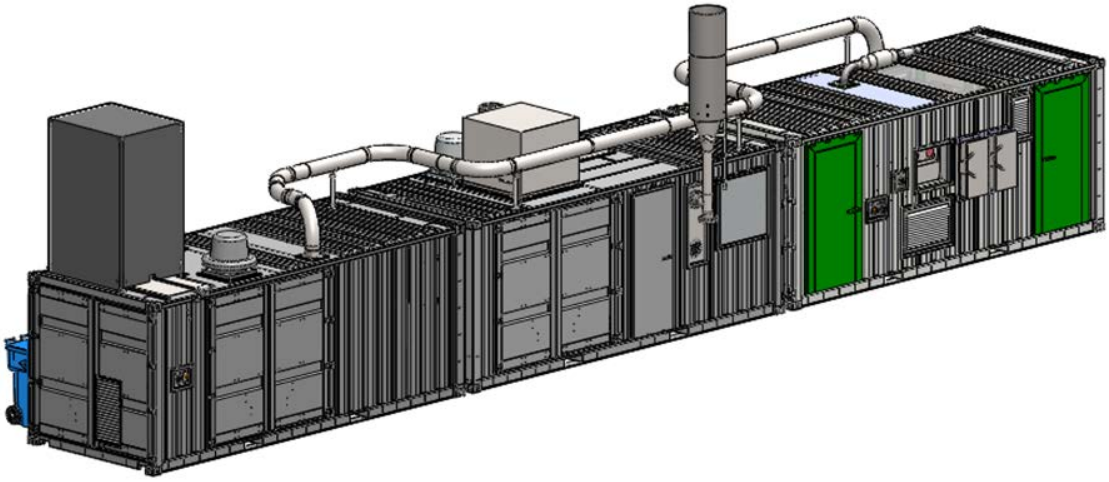


Figure 47. Integrated containerized waste to energy conversion system featuring shredded waste gasifier – three dimensional view from end one.

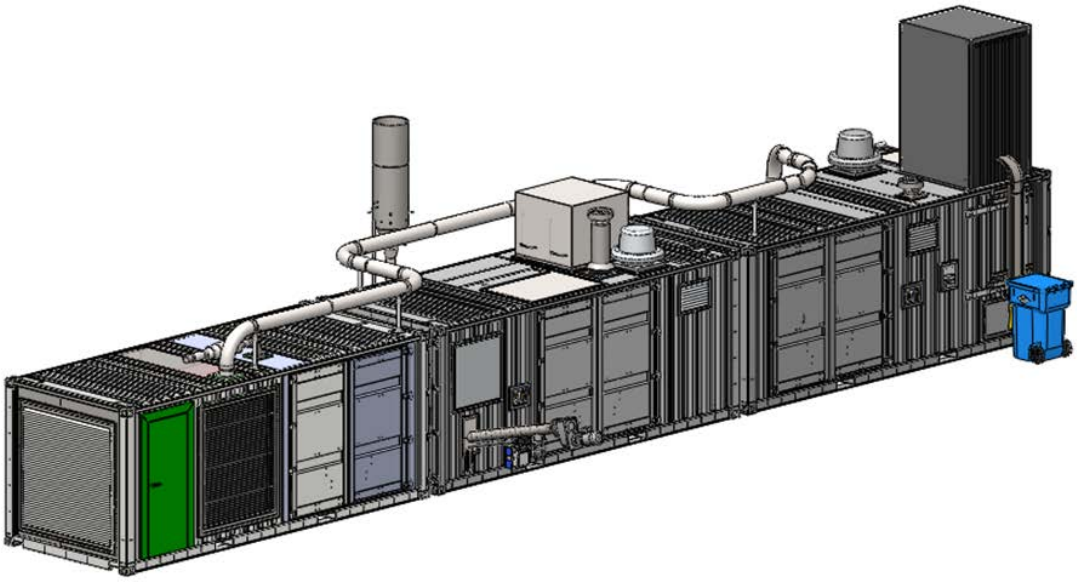


Figure 48. Integrated containerized waste to energy conversion system featuring shredded waste gasifier – three dimensional view from end two.

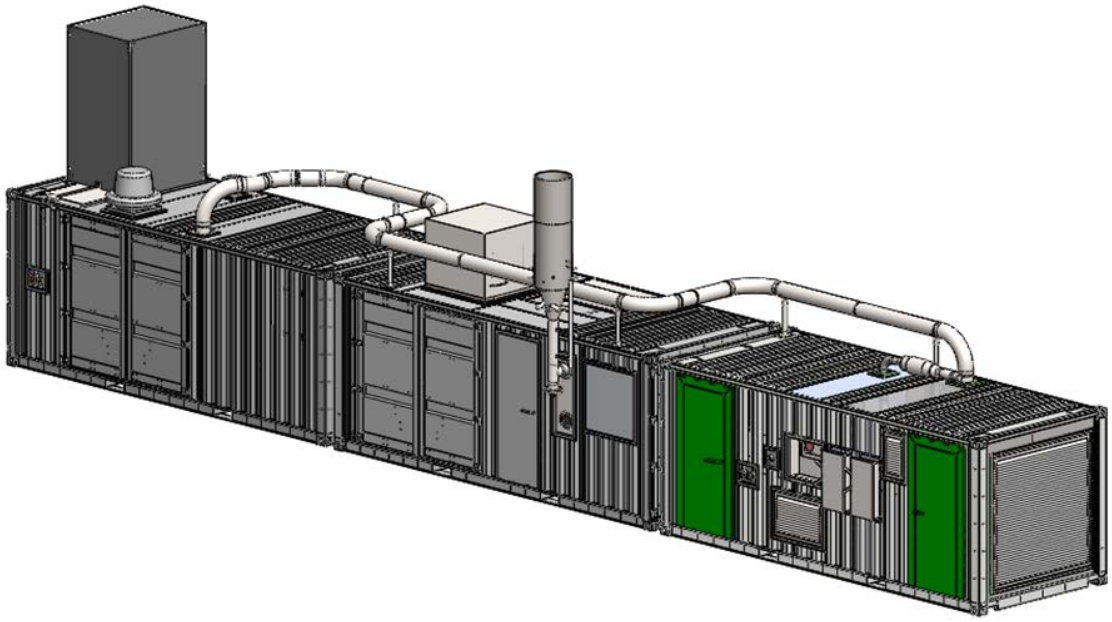


Figure 49. Integrated containerized waste to energy conversion system featuring shredded waste gasifier – three dimensional view from end two, alternate side.

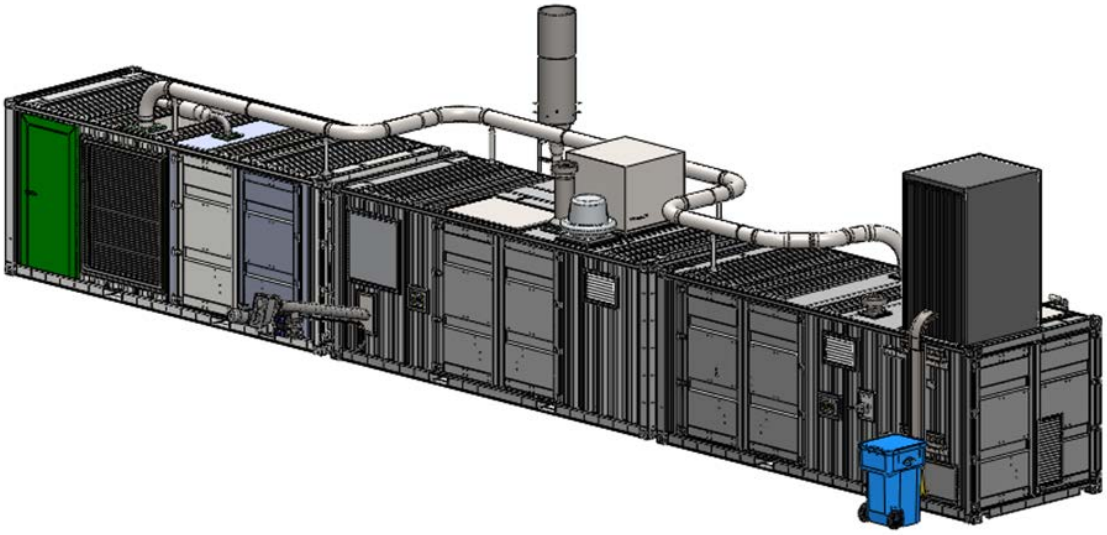


Figure 50. Integrated containerized waste to energy conversion system featuring shredded waste gasifier – three dimensional view from end one, alternate side.

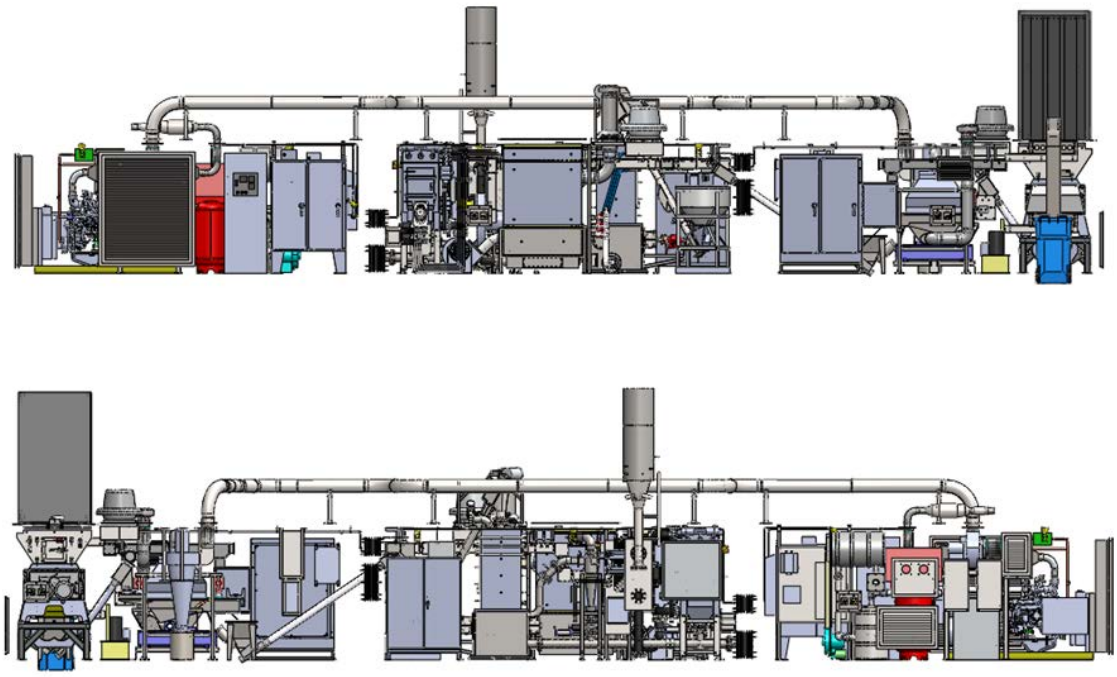


Figure 51. Integrated waste to energy conversion system featuring shredded waste gasifier – internal view of equipment from both sides.

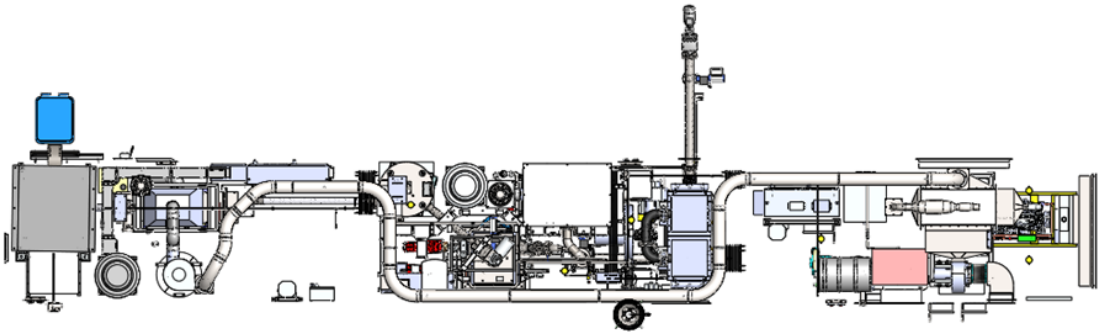


Figure 52. Integrated waste to energy conversion system featuring shredded waste gasifier – internal view of equipment, alternate side view.

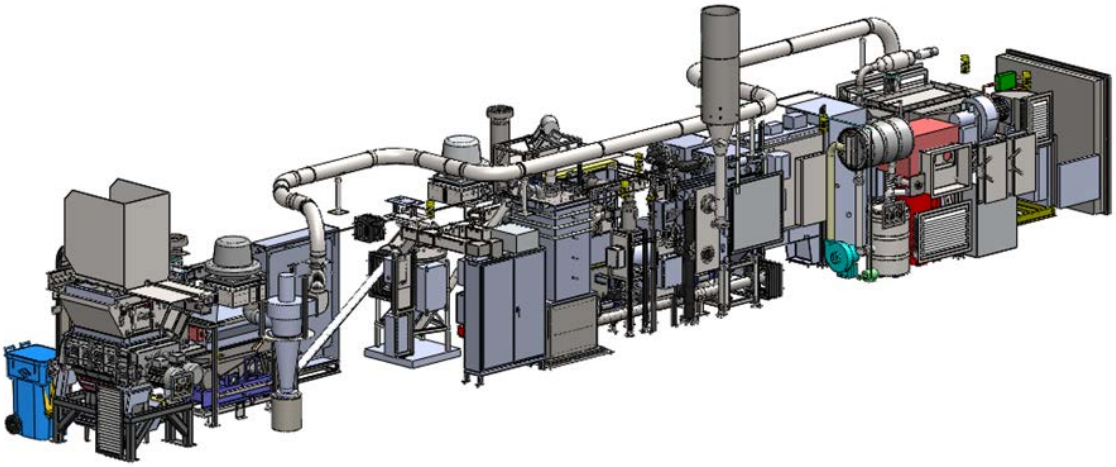


Figure 53. Integrated waste to energy conversion system featuring shredded waste gasifier – internal view of equipment, three dimensional view from end one.

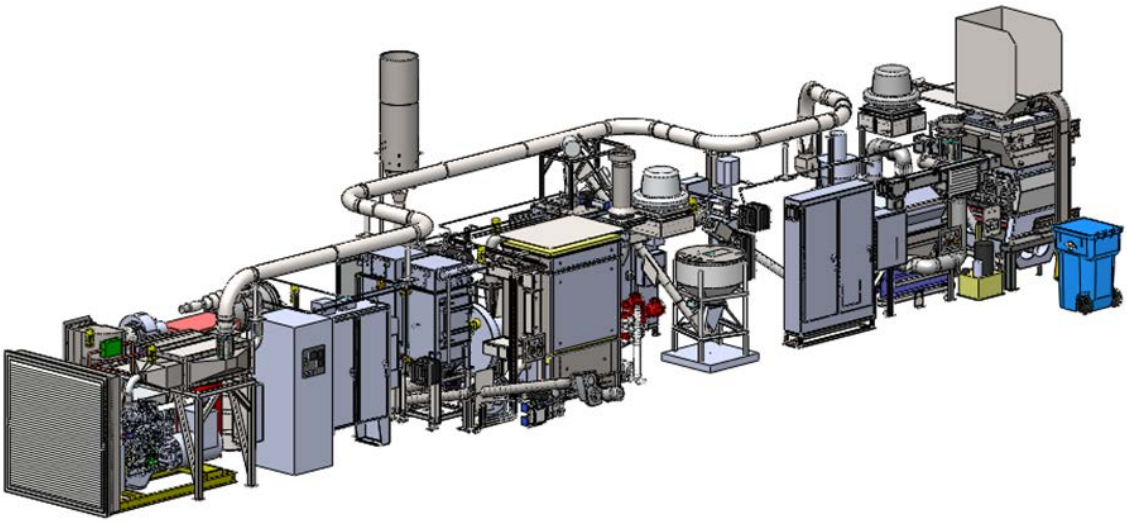


Figure 54. Integrated waste to energy conversion system featuring shredded waste gasifier – internal view of equipment, three dimensional view from end two.

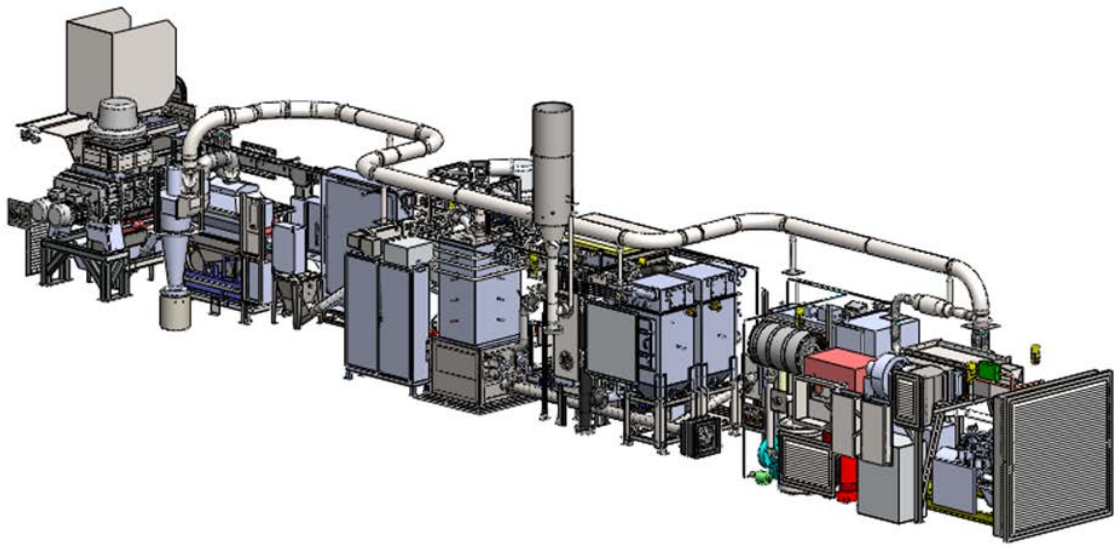


Figure 55. Integrated waste to energy conversion system featuring shredded waste gasifier – internal view of equipment, three dimensional view from end two, other side.

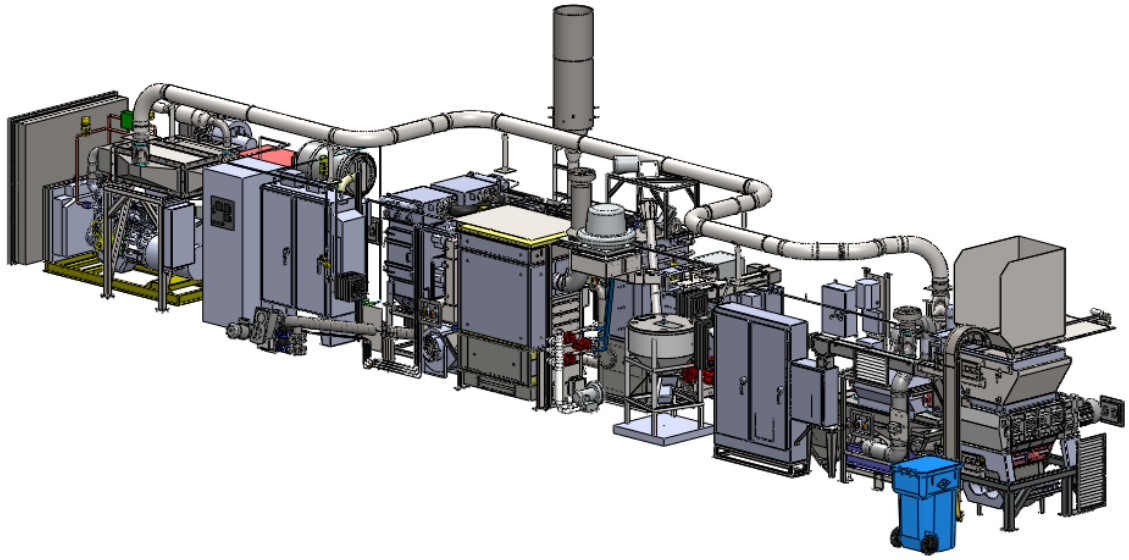


Figure 56. Integrated waste to energy conversion system featuring shredded waste gasifier – internal view of equipment, three dimensional view from end one, other side.

7 LITERATURE CITED

1. Reed, T.B. and Das, A., "Handbook of Biomass Downdraft Gasifier Engine Systems," Second Printing, The Biomass Energy Foundation Press, Golden, CO, 1988.
2. Reed, T.B., Graboski, M.S. and Levie, B., "Fundamentals, Development and Scale-up of the Air-Oxygen Stratified Downdraft Gasifier," SERI/PR-234-2571, The Biomass Energy Foundation Press, Golden, CO, 1986.
3. ASTM D6128-06, "Standard Test Method for Shear Testing of Bulk Solids Using the Jenike Shear Cell," ASTM International, West Conshohocken, PA, 2006.
4. Jenike, A.W., "Storage and Flow of Solids," Bulletin 123, University of Utah Engineering Station, 1964 (revised, 1976).
5. https://www.solidworks.com/sw/products/simulation/flow-simulation.htm; http://www.solidworks.com/sw/support/808_ENU_HTML.htm
6. Probstein, R.F., Physicochemical Hydrodynamics, Butterworths, Stoneham, MA, 1989.
7. Probstein, R.F. and Hicks, R.E., Synthetic Fuels, McGraw-Hill Book Company, New York, NY, 1982.
8. Basu, P., Biomass Gasification and Pyrolysis – Practical Design and Theory, Academic Press, Elsevier, 2010

APPENDIX A: SUPPORTING DATA

A1 Shredded Waste Material Flow Characterization Data

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

SUMMARY OF TESTS PERFORMED

This report presents various flow property test results as indicated for the following material(s) :

BULK MATERIAL	MATERIAL ID #	DESCRIPTION	PARTICLE SIZE	MOISTURE CONTENT
1	29179	Shredded Waste 1 (20mm 10%mc)	20mm (As Rec'd)	As Rec'd
2	29180	Shredded Waste 3 (20mm 20%mc)	20mm (As Rec'd)	As Rec'd
3	29181	Shredded Waste 4 (15mm 10%mc)	15mm (As Rec'd)	As Rec'd

BULK MATERIAL	TIME hr	TEMPERATURE deg F	SIEVE ANALYSIS	BIN DIM	BULK DENSITY	HOPPER ANGLES	CHUTE ANGLES	FLOW RATE	OTHER
1	0.0	72		X	X	X		X	X
2	0.0	72		X	X	X		X	X
3	0.0	72		X	X	X		X	X

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL 1: Shredded Waste 1 (20mm 10%mc)

PARTICLE SIZE 20mm (As Rec'd)

MOISTURE CONTENT As Rec'd

SECTION I. BIN DIMENSIONS FOR DEPENDABLE FLOW

Storage Time at Rest 0.0 hrs
Temperature 72 deg F

PART A. BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

P-Factor	BC feet	BP feet
1.00	0.3	0.2
1.25	0.4	0.2
1.50	0.5	0.2
2.00	1.4	0.5

Funnel Flow Dimensions

P-Factor	BF (feet)	EH=	0.5	1.0	2.5	5	9 feet
			Critical Rathole Diameters, DF (feet)				
1.00	0.2		0.9	1.4	3.2	6	11
1.25	0.3						
1.50	0.5						
2.00	***						

*** Denotes unassisted gravity flow is impossible. However, widths of only up to 3.7 feet were simulated by our tests. If larger widths are practical for your application, further testing at higher pressures might reveal conditions under which unassisted gravity flow is possible.

TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectangular outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL 1: Shredded Waste 1 (20mm 10%mc)

PARTICLE SIZE 20mm (As Rec'd)

MOISTURE CONTENT As Rec'd

SECTION II. SOLIDS DENSITY

TEMPERATURE 72 deg F

BULK DENSITY
The bulk density, GAMMA, is a function of the major consolidating pressure, SIGMA1, expressed in terms of effective head, EH.

EH (feet)	0.5	1.0	2.5	5.0	10.0	20.0	40.0	80.0
SIGMA1 (psf)	6.	12.	33.	72.	165.	382.	894.	2106.
GAMMA (pcf)	11.7	12.1	13.1	14.5	16.5	19.1	22.4	26.3

COMPRESSIBILITY PARAMETERS

Bulk density, GAMMA, is a function of the major consolidating pressure SIGMA1, as follows:

$$GAMMA = GAMMAM\ (SIGMA1/SIGMAM + 1)^{BETAM}$$

For GAMMA between 12.8 and 27.5 pcf

Minimum bulk density GAMMAM = 11.2 pcf

SIGMAM = 26.68 psf

BETAM = 0.19459

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL 1: Shredded Waste 1 (20mm 10%mc)

PARTICLE SIZE 20mm (As Rec'd)

MOISTURE CONTENT As Rec'd

SECTION III. MAXIMUM HOPPER ANGLES FOR MASS FLOW

WALL MATERIAL: Polished Refractory
STORAGE TIME AT REST 0.0 hrs
TEMPERATURE 72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)	0.94	2.00	4.00	8.00	14.93
Width of Oval (feet)	0.50	1.07	2.14	4.27	7.88
SIGMA (psf)	4.0	9.0	19.	44.	95.
SIGMA1 (psf)	7.0	15.7	34.	73.	149.
Wall Friction Angle					
PHI-PRIME (deg)	38.	38.	37.	36.	33.
Hopper Angles					
THETA-P (deg)	11.*	11.*	11.*	12.	16.
THETA-C (deg)	1.*	1.*	1.*	2.	5.

* Flow along walls is questionable.

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL 1: Shredded Waste 1 (20mm 10%mc)

PARTICLE SIZE 20mm (As Rec'd)

MOISTURE CONTENT As Rec'd

SECTION IV. CRITICAL STEADY SOLIDS FLOW RATES IN AIR

TEMPERATURE 72.0 deg F

CONICAL MASS FLOW HOPPER

Flow rate expressed in units of tons/hr.

BC	EH = 2.5 feet	5.0 feet	10.0 feet	20.0 feet	40.0 feet
0.50 feet	8.8	7.9	7.0	6.3	5.7
0.75 feet	28.	25.	23.	19.	18.
1.00 feet	61.	54.	48.	43.	37.
2.00 feet	360.	306.	270.	234.	198.
4.00 feet	1980.	1584.	1296.	1080.	936.
8.00 feet	9720.	7560.	5940.	4860.	4140.

TRANSITION MASS FLOW HOPPER

Flow rate expressed in units of tons/hr per feet length of outlet.

BP	EH = 2.5 feet	5.0 feet	10.0 feet	20.0 feet	40.0 feet
0.25 feet	7.0	6.4	5.9	5.4	4.9
0.50 feet	27.	25.	23.	21.	19.
0.75 feet	52.	48.	43.	39.	36.
1.00 feet	82.	73.	66.	59.	54.
2.00 feet	234.	198.	171.	149.	131.
4.00 feet	612.	504.	414.	342.	306.
8.00 feet	1530.	1206.	936.	774.	648.

TERMS

BC = diameter of circular outlet
BP = width of slotted outlet
EH = effective consolidating head

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL 1: Shredded Waste 1 (20mm 10%mc)

PARTICLE SIZE 20mm (As Rec'd)

MOISTURE CONTENT As Rec'd

SECTION V. AIR PERMEABILITY TEST RESULTS

Temperature of test 68 deg F

K, the AIR permeability factor of the solid is defined from Darcy's law in the following form:

$$K = -u\ (GAMMA)\ /\ (dp/dx)$$

where:

u = superficial AIR velocity through the bed of solids

dp/dx = AIR pressure gradient across the bed

GAMMA = bulk density of the solid in the bed

K is a function of the bulk density of the solid

$$K = K0\ (GAMMA\ /\ GAMMA0)^{-a}$$

At room temperature, for GAMMA between 11.2 and 21.8 pcf:

K0 = 1.819947 ft/s

GAMMA0 = 12.1 pcf

a = 2.60

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL 2: Shredded Waste 3 (20mm 20%mc)

PARTICLE SIZE 20mm (As Rec'd)

MOISTURE CONTENT As Rec'd

SECTION I. BIN DIMENSIONS FOR DEPENDABLE FLOW

Storage Time at Rest 0.0 hrs
Temperature 72 deg F

PART A. BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

P-Factor	BC feet	BP feet
1.00	0.3	0.1
1.25	0.4	0.2
1.50	0.4	0.2
2.00	0.8	0.3

Funnel Flow Dimensions

P-Factor	BF (feet)	EH=	0.5	1.0	2.5	5	7 feet
			Critical Rathole Diameters, DF (feet)				
1.00	0.2		1.1	1.8	3.7	6	8
1.25	0.3						
1.50	0.5						
2.00	***						

*** Denotes unassisted gravity flow is impossible. However, widths of only up to 3.0 feet were simulated by our tests. If larger widths are practical for your application, further testing at higher pressures might reveal conditions under which unassisted gravity flow is possible.

TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectangular outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL 2: Shredded Waste 3 (20mm 20%mc)

PARTICLE SIZE 20mm (As Rec'd)

MOISTURE CONTENT As Rec'd

SECTION II. SOLIDS DENSITY

TEMPERATURE 72 deg F

BULK DENSITY
The bulk density, GAMMA, is a function of the major consolidating pressure, SIGMA1, expressed in terms of effective head, EH.

EH (feet)	0.5	1.0	2.5	5.0	10.0	20.0	40.0	80.0
SIGMA1 (psf)	7.	14.	39.	86.	200.	485.	1207.	3039.
GAMMA (pcf)	14.0	14.4	15.5	17.2	20.0	24.3	30.2	38.0

COMPRESSIBILITY PARAMETERS

Bulk density, GAMMA, is a function of the major consolidating pressure SIGMA1, as follows:

$$GAMMA = GAMMAM\ (SIGMA1/SIGMAM + 1)^{BETAM}$$

For GAMMA between 15.1 and 35.6 pcf

Minimum bulk density GAMMAM = 13.6 pcf

SIGMAM = 56.41 psf

BETAM = 0.25704

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL 2: Shredded Waste 3 (20mm 20%mc)

PARTICLE SIZE 20mm (As Rec'd)

MOISTURE CONTENT As Rec'd

SECTION III. MAXIMUM HOPPER ANGLES FOR MASS FLOW

WALL MATERIAL: Polished Refractory
STORAGE TIME AT REST 0.0 hrs
TEMPERATURE 72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)	0.85	2.00	4.00	8.00	12.89
Width of Oval (feet)	0.47	1.09	2.15	4.25	6.82
SIGMA (psf)	4.2	10.7	23.	53.	96.
SIGMA1 (psf)	6.4	16.3	36.	84.	153.
Wall Friction Angle					
PHI-PRIME (deg)	35.	34.	34.	34.	34.
Hopper Angles					
THETA-P (deg)	15.	15.	15.	15.	15.
THETA-C (deg)	4.	4.	4.	4.	4.

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL 2: Shredded Waste 3 (20mm 20%mc)

PARTICLE SIZE 20mm (As Rec'd)

MOISTURE CONTENT As Rec'd

SECTION IV. CRITICAL STEADY SOLIDS FLOW RATES IN AIR

TEMPERATURE 72.0 deg F

CONICAL MASS FLOW HOPPER

Flow rate expressed in units of tons/hr.

BC	EH = 2.5 feet	5.0 feet	10.0 feet	20.0 feet	40.0 feet
0.50 feet	11.	11.	10.	9.7	9.0
0.75 feet	37.	36.	34.	30.	28.
1.00 feet	82.	79.	72.	66.	63.
2.00 feet	504.	468.	414.	378.	342.
4.00 feet	2880.	2520.	2160.	1980.	1746.
8.00 feet	*****	*****	*****	9540.	8280.

TRANSITION MASS FLOW HOPPER

Flow rate expressed in units of tons/hr per feet length of outlet.

BP	EH = 2.5 feet	5.0 feet	10.0 feet	20.0 feet	40.0 feet
0.25 feet	9.0	8.6	8.2	7.7	7.4
0.50 feet	36.	34.	32.	30.	28.
0.75 feet	70.	66.	63.	59.	55.
1.00 feet	109.	104.	97.	91.	84.
2.00 feet	324.	288.	270.	252.	234.
4.00 feet	882.	810.	702.	630.	558.
8.00 feet	2340.	2160.	1782.	1512.	1314.

***** Denotes extremely high flow rate.

TERMS

BC = diameter of circular outlet
BP = width of slotted outlet
EH = effective consolidating head

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL 2: Shredded Waste 3 (20mm 20%mc)

PARTICLE SIZE 20mm (As Rec'd)

MOISTURE CONTENT As Rec'd

SECTION V. AIR PERMEABILITY TEST RESULTS

Temperature of test 68 deg F

K, the AIR permeability factor of the solid is defined from Darcy's law in the following form:

$$K = -u\ (GAMMA)\ /\ (dp/dx)$$

where:

u = superficial AIR velocity through the bed of solids

dp/dx = AIR pressure gradient across the bed

GAMMA = bulk density of the solid in the bed

K is a function of the bulk density of the solid

$$K = K0\ (GAMMA\ /\ GAMMA0)^{-a}$$

At room temperature, for GAMMA between 16.3 and 29.2 pcf:

K0 = 4.002043 ft/s

GAMMA0 = 14.3 pcf

a = 3.31

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL 3: Shredded Waste 4 (15mm 10%mc)

PARTICLE SIZE 15mm (As Rec'd)

MOISTURE CONTENT As Rec'd

SECTION I. BIN DIMENSIONS FOR DEPENDABLE FLOW

Storage Time at Rest 0.0 hrs
Temperature 72 deg F

PART A. BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

P-Factor	BC feet	BP feet
1.00	0.9	0.5
1.25	1.0	0.5
1.50	1.2	0.6
2.00	1.6	0.7

Funnel Flow Dimensions

P-Factor	BF (feet)	EH=	0.5	1.0	2.5	5	9 feet
			Critical Rathole Diameters, DF (feet)				
1.00	0.5		1.8	2.4	4.0	7	11
1.25	0.6						
1.50	0.8						
2.00	1.7						

TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectangular outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL 3: Shredded Waste 4 (15mm 10%mc)

PARTICLE SIZE 15mm (As Rec'd)

MOISTURE CONTENT As Rec'd

SECTION II. SOLIDS DENSITY

TEMPERATURE 72 deg F

BULK DENSITY
The bulk density, GAMMA, is a function of the major consolidating pressure, SIGMA1, expressed in terms of effective head, EH.

EH (feet)	0.5	1.0	2.5	5.0	10.0	20.0	40.0	80.0
SIGMA1 (psf)	5.	10.	28.	66.	155.	370.	888.	2137.
GAMMA (pcf)	9.2	9.8	11.3	13.1	15.5	18.5	22.2	26.7

COMPRESSIBILITY PARAMETERS

Bulk density, GAMMA, is a function of the major consolidating pressure SIGMA1, as follows:

$$GAMMA = GAMMAM\ (SIGMA1/SIGMAM + 1)^{BETAM}$$

For GAMMA between 11.1 and 27.1 pcf

Minimum bulk density GAMMAM = 8.5 pcf

SIGMAM = 9.53 psf

BETAM = 0.21225

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL 3: Shredded Waste 4 (15mm 10%mc)

PARTICLE SIZE 15mm (As Rec'd)

MOISTURE CONTENT As Rec'd

SECTION III. MAXIMUM HOPPER ANGLES FOR MASS FLOW

WALL MATERIAL: Polished Refractory
STORAGE TIME AT REST 0.0 hrs
TEMPERATURE 72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)	1.19	2.00	4.00	8.00	16.19
Width of Oval (feet)	0.64	1.08	2.17	4.33	8.62
SIGMA (psf)	3.9	7.1	16.	37.	95.
SIGMA1 (psf)	7.0	12.5	28.	65.	147.
Wall Friction Angle					
PHI-PRIME (deg)	40.	40.	39.	37.	34.
Hopper Angles					
THETA-P (deg)	10.*	10.*	10.*	10.	15.
THETA-C (deg)	0.*	0.*	0.*	1.	6.

* Flow along walls is questionable.

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL 3: Shredded Waste 4 (15mm 10%mc)

PARTICLE SIZE 15mm (As Rec'd)

MOISTURE CONTENT As Rec'd

SECTION IV. CRITICAL STEADY SOLIDS FLOW RATES IN AIR

TEMPERATURE 72.0 deg F

CONICAL MASS FLOW HOPPER

Flow rate expressed in units of tons/hr.

BC	EH = 2.5 feet	5.0 feet	10.0 feet	20.0 feet	40.0 feet
1.00 feet	14.	10.	8.2	6.8	6.0
1.50 feet	72.	55.	45.	39.	34.
2.00 feet	169.	131.	106.	90.	79.
4.00 feet	1008.	756.	594.	504.	432.
8.00 feet	5040.	3600.	2880.	2340.	1980.

TRANSITION MASS FLOW HOPPER

Flow rate expressed in units of tons/hr per feet length of outlet.

BP	EH = 2.5 feet	5.0 feet	10.0 feet	20.0 feet	40.0 feet
0.50 feet	0.61	0.41	0.31	0.25	0.22
0.75 feet	19.	16.	13.	11.	10.
1.00 feet	39.	32.	27.	23.	21.
1.50 feet	81.	64.	54.	46.	41.
2.00 feet	127.	102.	82.	72.	63.
4.00 feet	342.	252.	216.	174.	153.
8.00 feet	828.	594.	468.	378.	342.

TERMS

BC = diameter of circular outlet
BP = width of slotted outlet
EH = effective consolidating head

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL 3: Shredded Waste 4 (15mm 10%mc)

PARTICLE SIZE 15mm (As Rec'd)

MOISTURE CONTENT As Rec'd

SECTION V. AIR PERMEABILITY TEST RESULTS

Temperature of test 68 deg F

K, the AIR permeability factor of the solid is defined from Darcy's law in the following form:

$$K = -u\ (GAMMA)\ /\ (dp/dx)$$

where:

u = superficial AIR velocity through the bed of solids

dp/dx = AIR pressure gradient across the bed

GAMMA = bulk density of the solid in the bed

K is a function of the bulk density of the solid

$$K = K0\ (GAMMA\ /\ GAMMA0)^{-a}$$

At room temperature, for GAMMA between 9.0 and 20.7 pcf:

K0 = 1.180936 ft/s

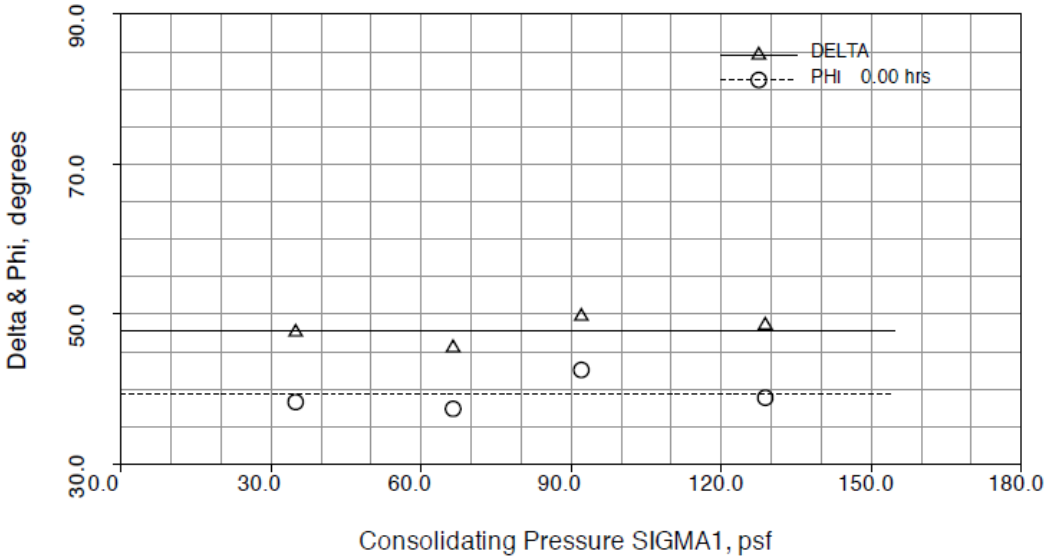
GAMMA0 = 10.2 pcf

a = 3.05

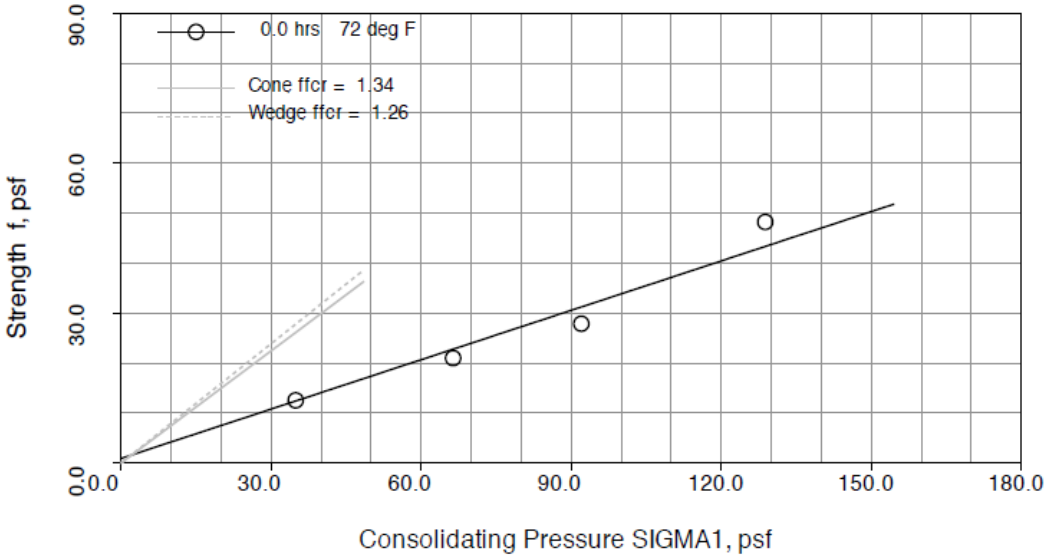
JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL: Shredded Waste 1 (20mm 10%mc)
PARTICLE SIZE: 20mm (As Rec'd) CREATE: 12/09/26 JOB#: 11201
MOISTURE % WT: As Rec'd RUN: 12/10/03 ID#: 29179

DELTA & PHI RELATIONS



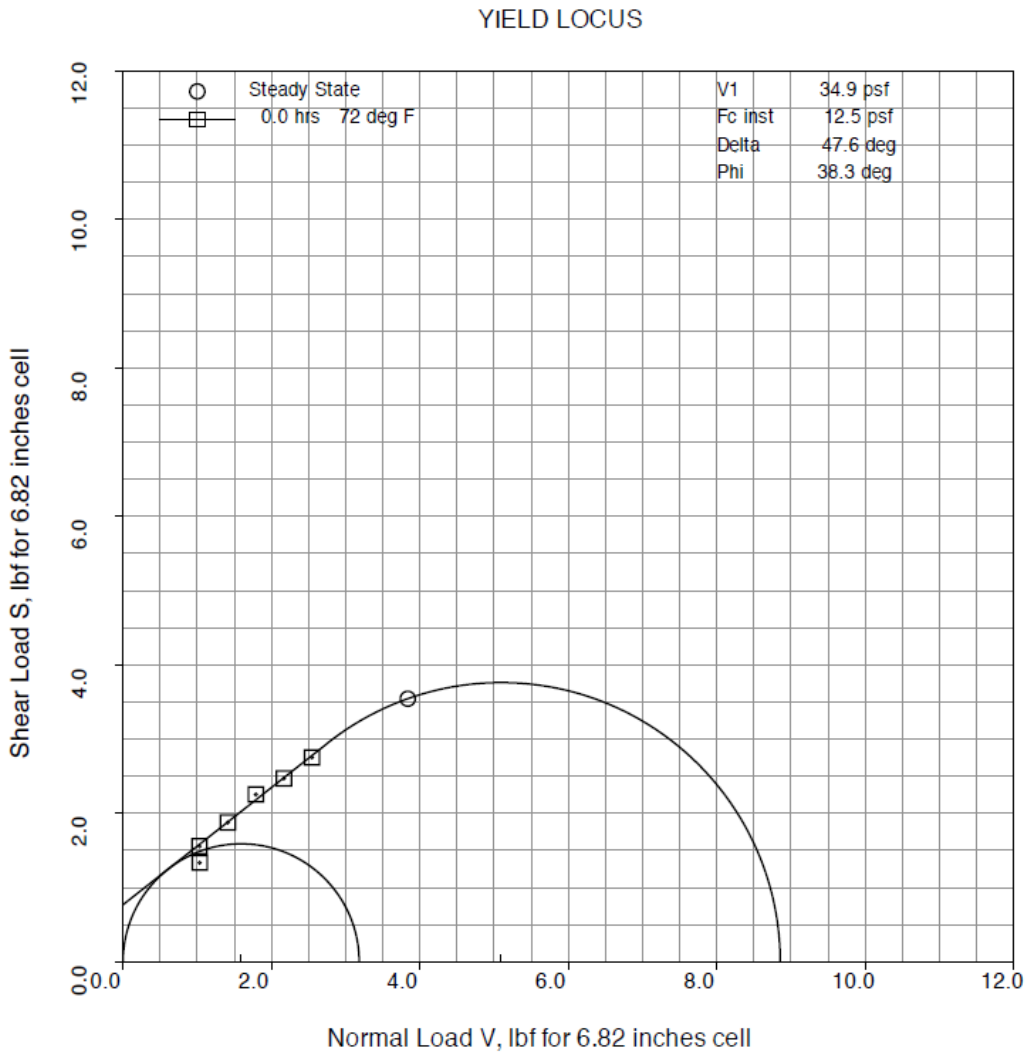
FLOW FUNCTION(S)



Plot 1

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

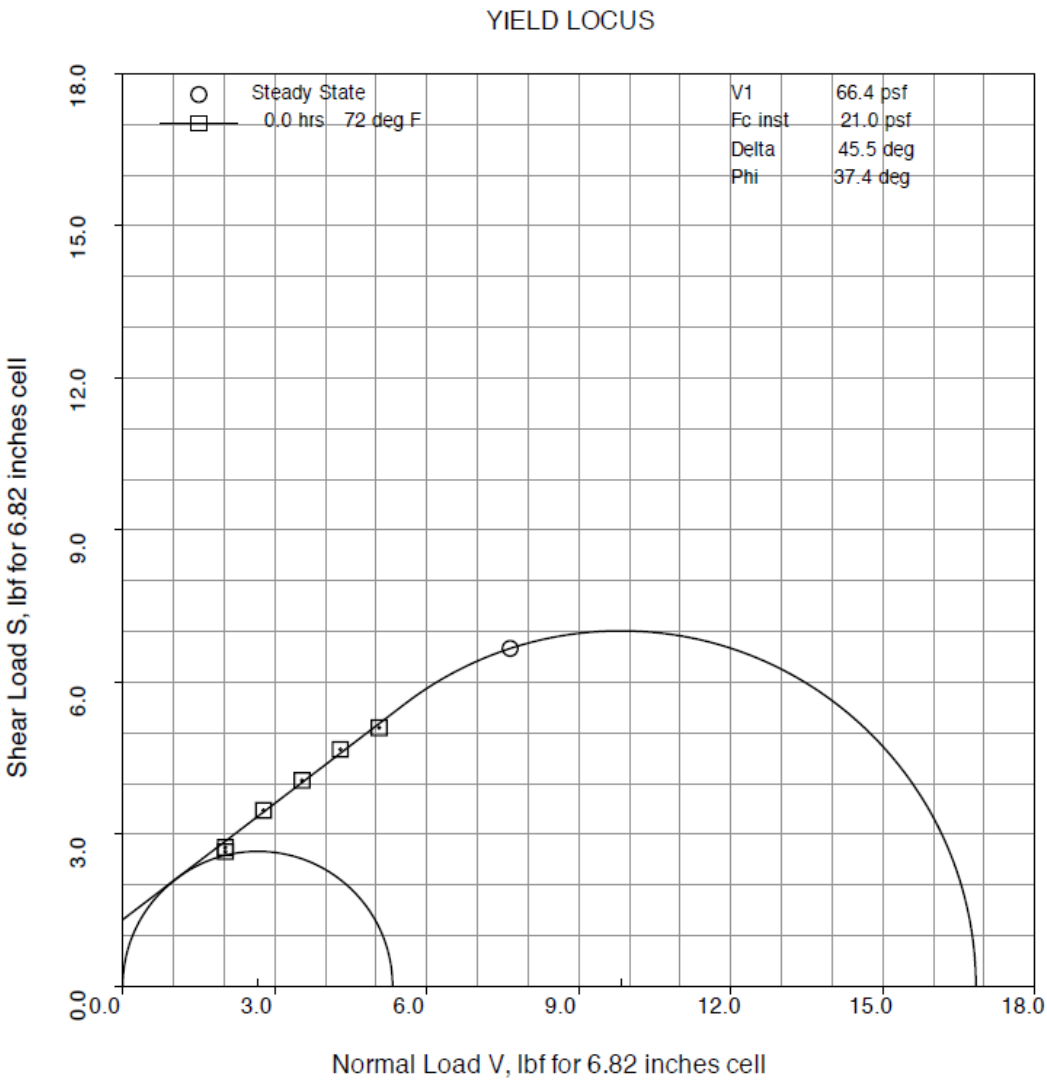
BULK MATERIAL: Shredded Waste 1 (20mm 10%mc)
PARTICLE SIZE: 20mm (As Rec'd) CREATE: 12/09/26 JOB#: 11201
MOISTURE % WT: As Rec'd RUN: 12/10/03 ID#: 29179



Plot 2

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL: Shredded Waste 1 (20mm 10%mc)
PARTICLE SIZE: 20mm (As Rec'd) CREATE: 12/09/26 JOB#: 11201
MOISTURE % WT: As Rec'd RUN: 12/10/03 ID#: 29179

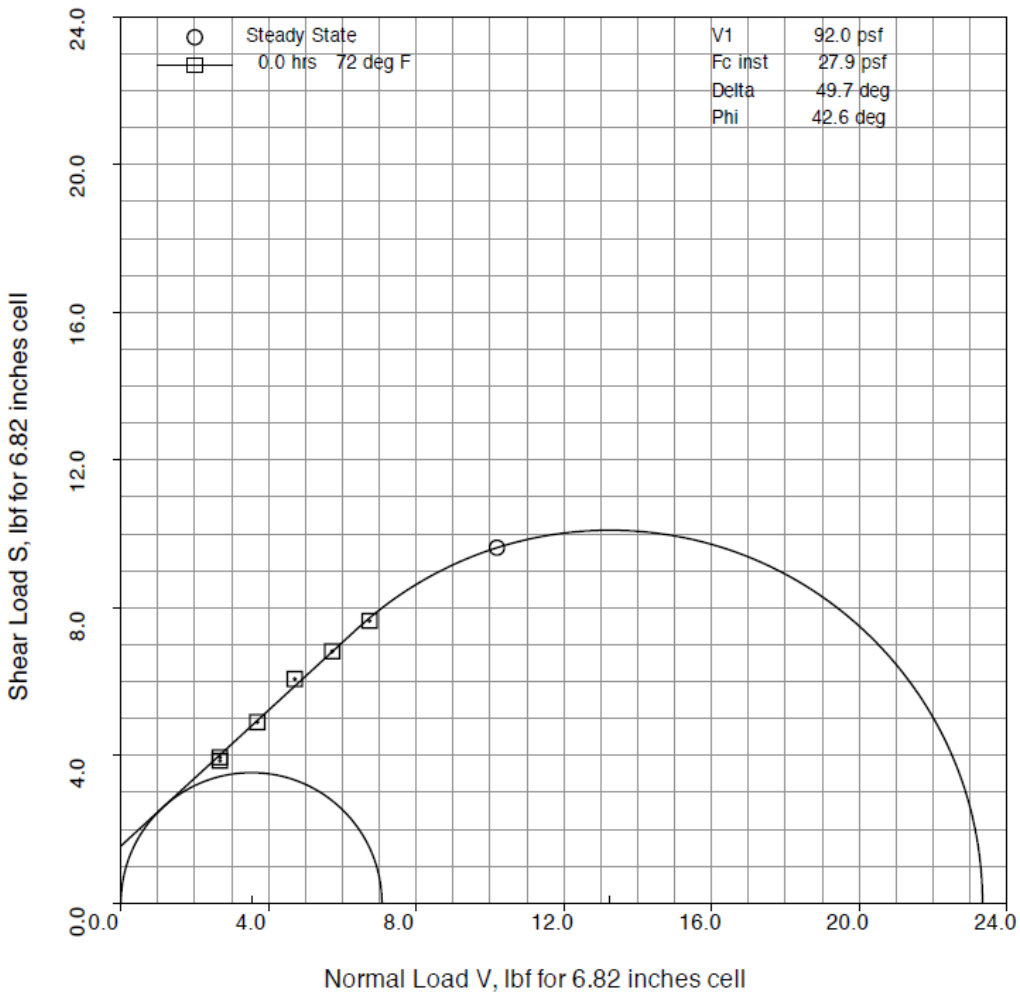


Plot 3

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL: Shredded Waste 1 (20mm 10%mc)
PARTICLE SIZE: 20mm (As Rec'd) CREATE: 12/09/26 JOB#: 11201
MOISTURE % WT: As Rec'd RUN: 12/10/03 ID#: 29179

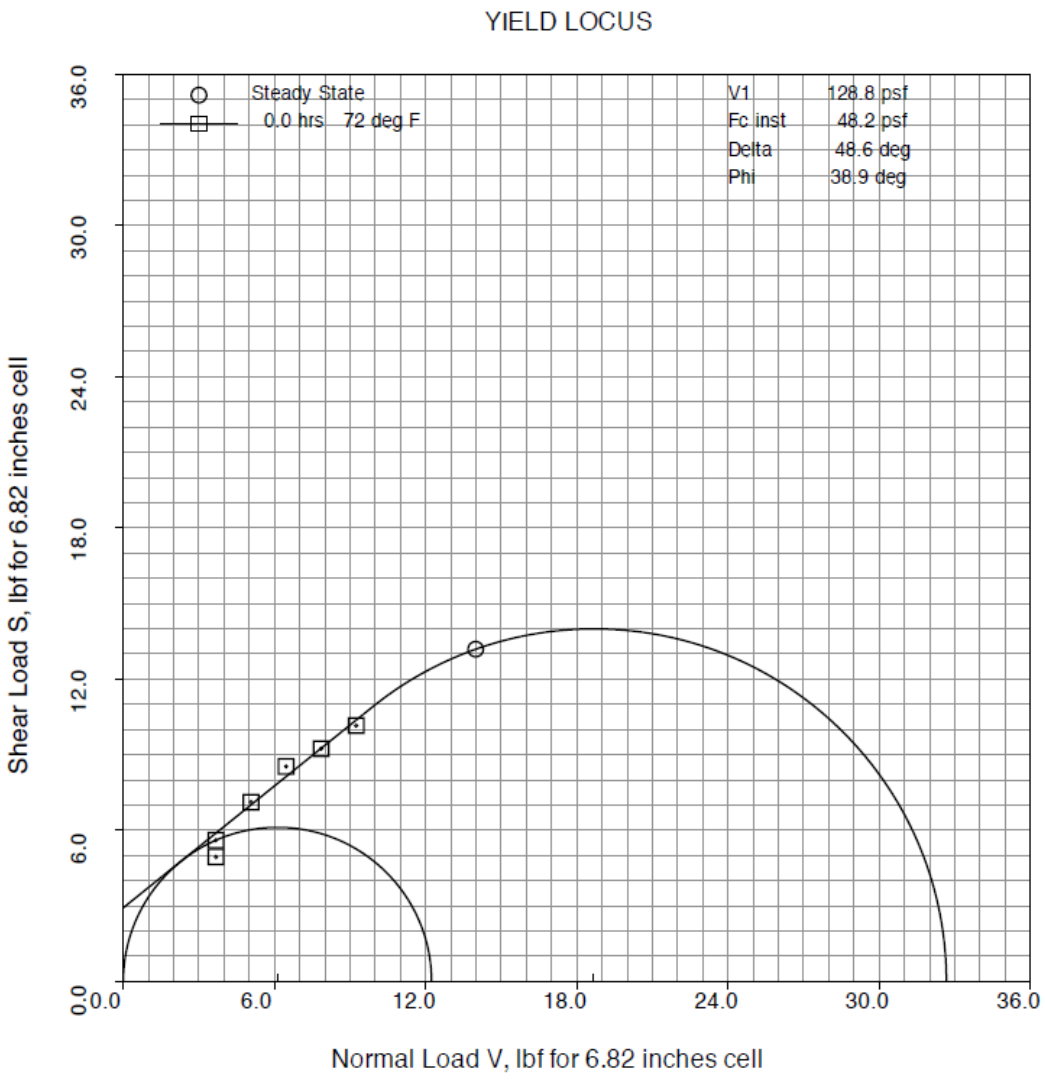
YIELD LOCUS



Plot 4

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL: Shredded Waste 1 (20mm 10%mc)
PARTICLE SIZE: 20mm (As Rec'd) CREATE: 12/09/26 JOB#: 11201
MOISTURE % WT: As Rec'd RUN: 12/10/03 ID#: 29179



Plot 5

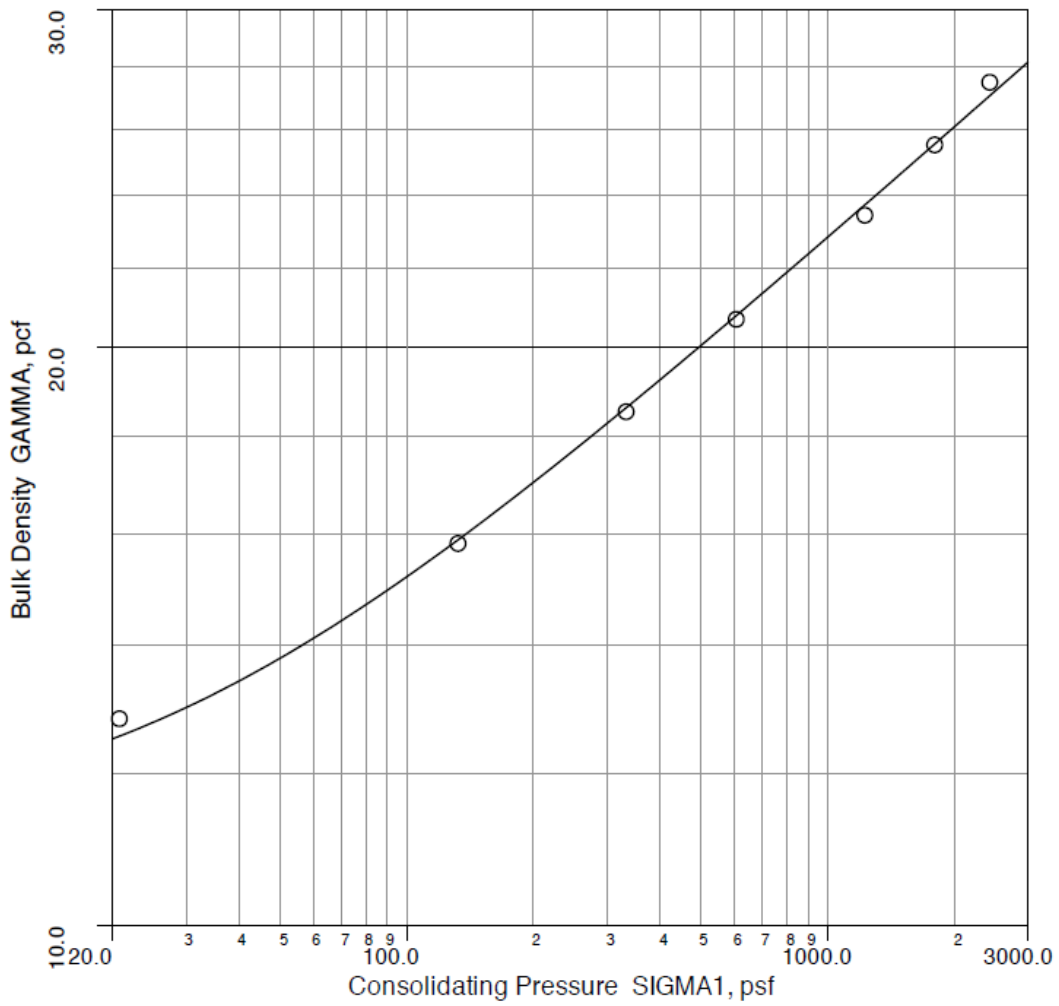
JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL: Shredded Waste 1 (20mm 10%mc)
PARTICLE SIZE: 20mm (As Rec'd)
MOISTURE % WT: As Rec'd
TEMPERATURE: 72 deg F

CREATE: 12/09/26
RUN: 12/10/03

JOB#: 11201
ID#: 29179

BULK DENSITY VS. CONSOLIDATING PRESSURE

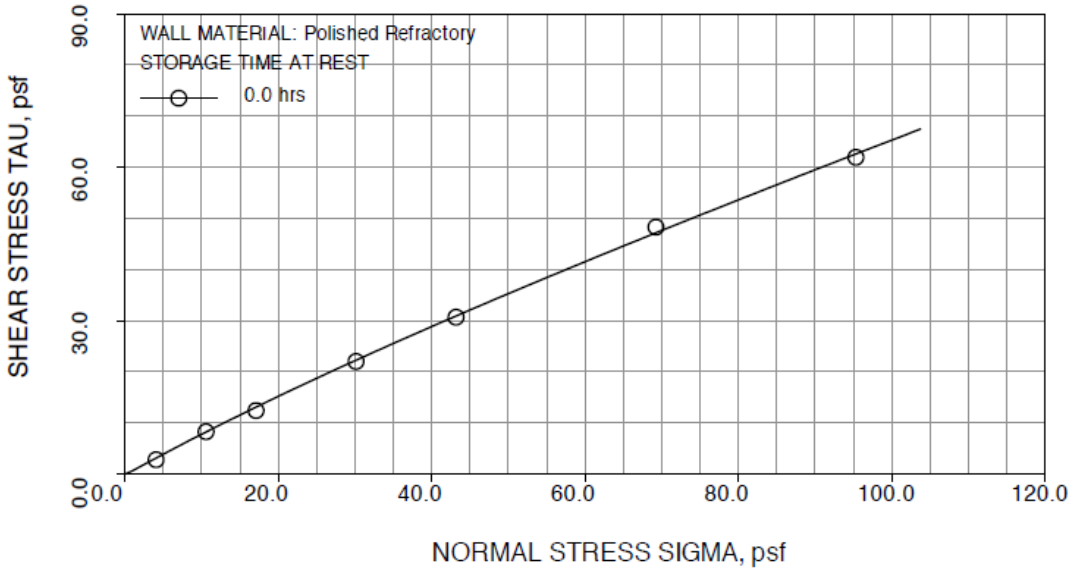


Plot 6

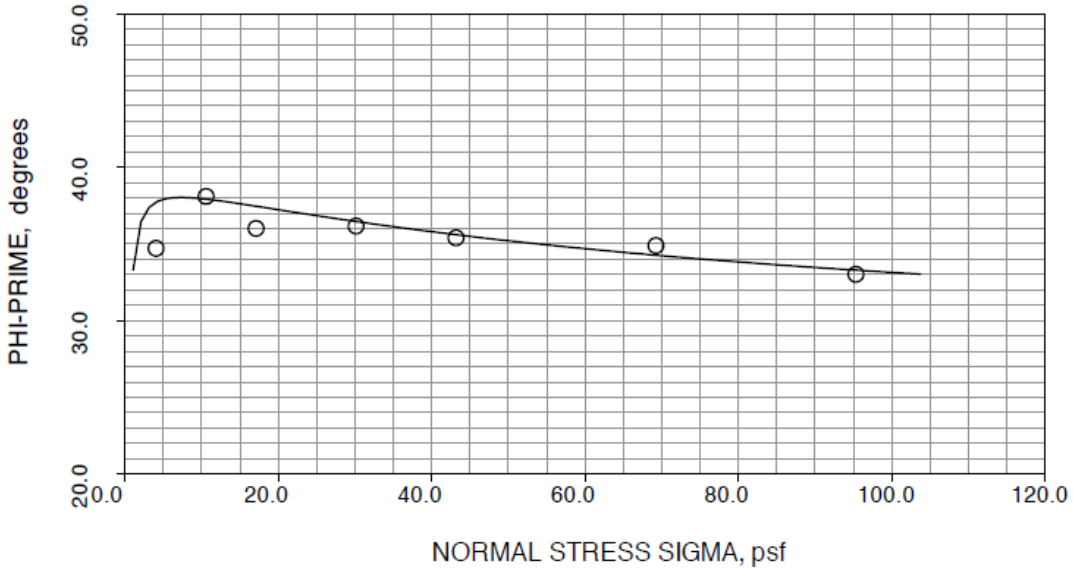
JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL: Shredded Waste 1 (20mm 10%mc)
PARTICLE SIZE: 20mm (As Rec'd) CREATE: 12/09/26 JOB#: 11201
MOISTURE % WT: As Rec'd RUN: 12/10/03 ID#: 29179
TEMPERATURE: 72 deg F

WALL YIELD LOCUS



WALL FRICTION ANGLE



Plot 7

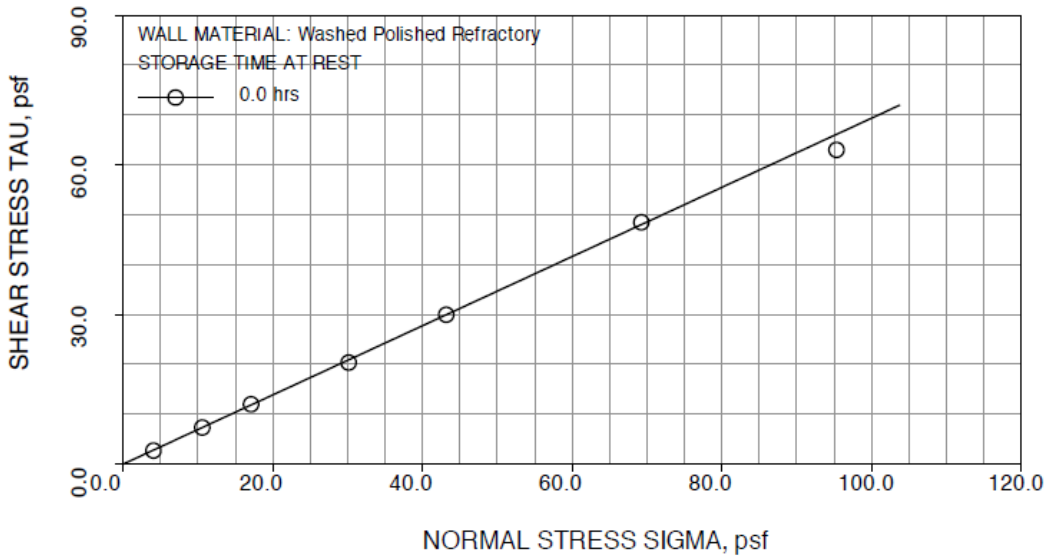
JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL: Shredded Waste 1 (20mm 10%mc)
PARTICLE SIZE: 20mm (As Rec'd)
MOISTURE % WT: As Rec'd
TEMPERATURE: 72 deg F

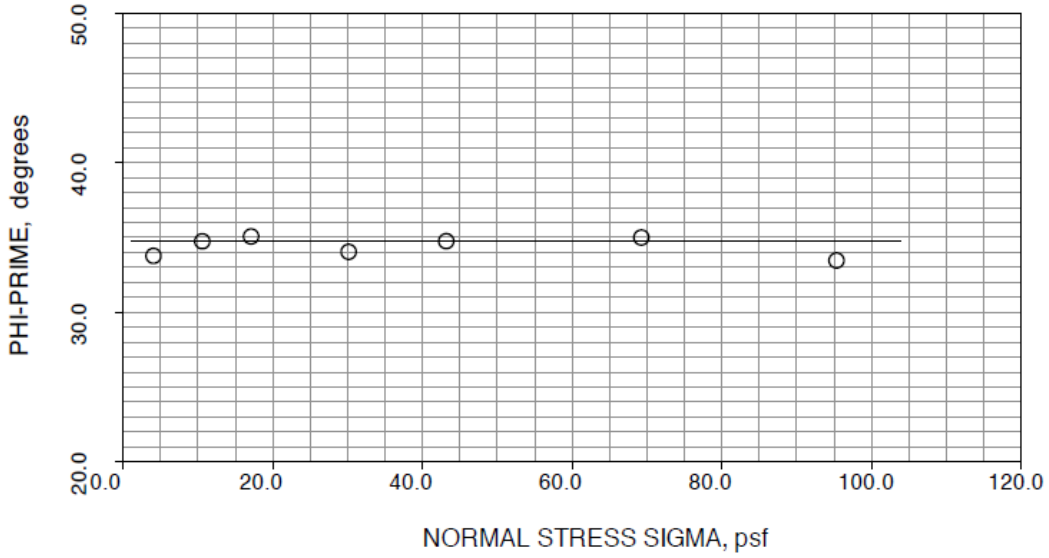
CREATE: 12/09/26
RUN: 12/10/03

JOB#: 11201
ID#: 29179

WALL YIELD LOCUS



WALL FRICTION ANGLE



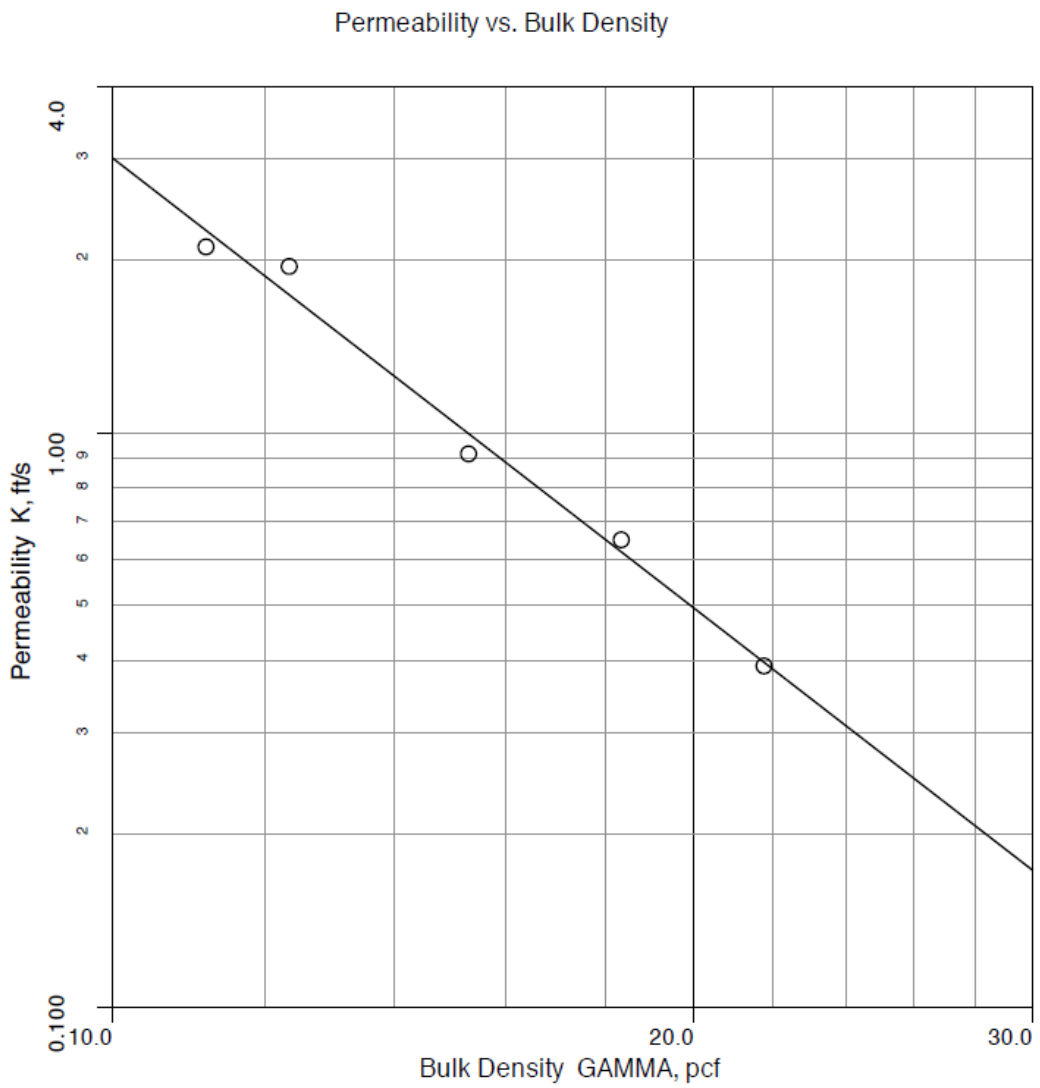
Plot 8

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL: Shredded Waste 1 (20mm 10%mc)
PARTICLE SIZE: 20mm (As Rec'd)
MOISTURE % WT: As Rec'd
TEMPERATURE: 68 deg F

CREATE: 12/09/26
RUN: 12/10/03

JOB#: 11201
ID#: 29179

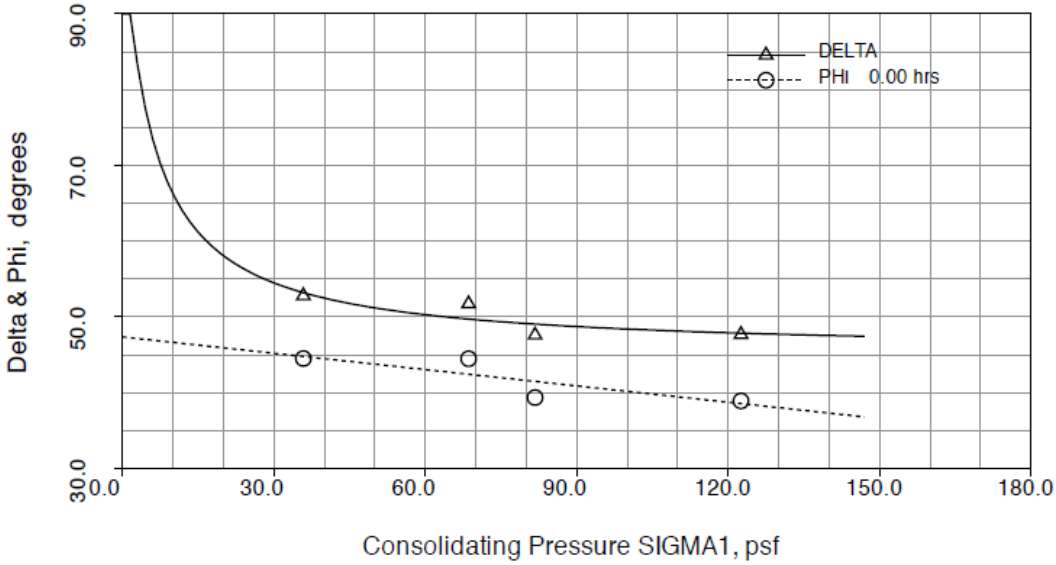


Plot 9

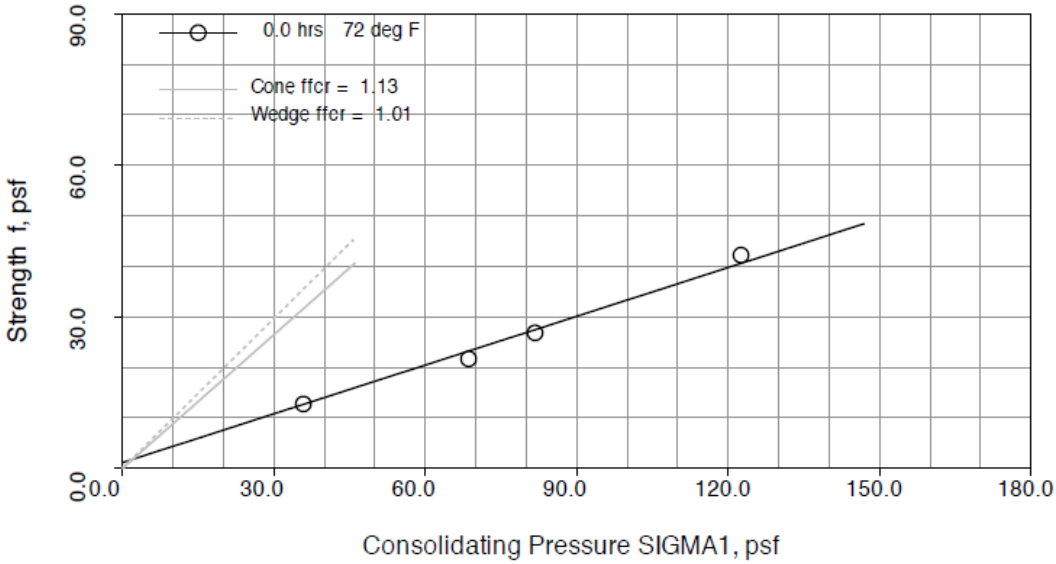
JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL: Shredded Waste 3 (20mm 20%mc)
PARTICLE SIZE: 20mm (As Rec'd) CREATE: 12/09/26 JOB#: 11201
MOISTURE % WT: As Rec'd RUN: 12/10/03 ID#: 29180

DELTA & PHI RELATIONS



FLOW FUNCTION(S)



Plot 10

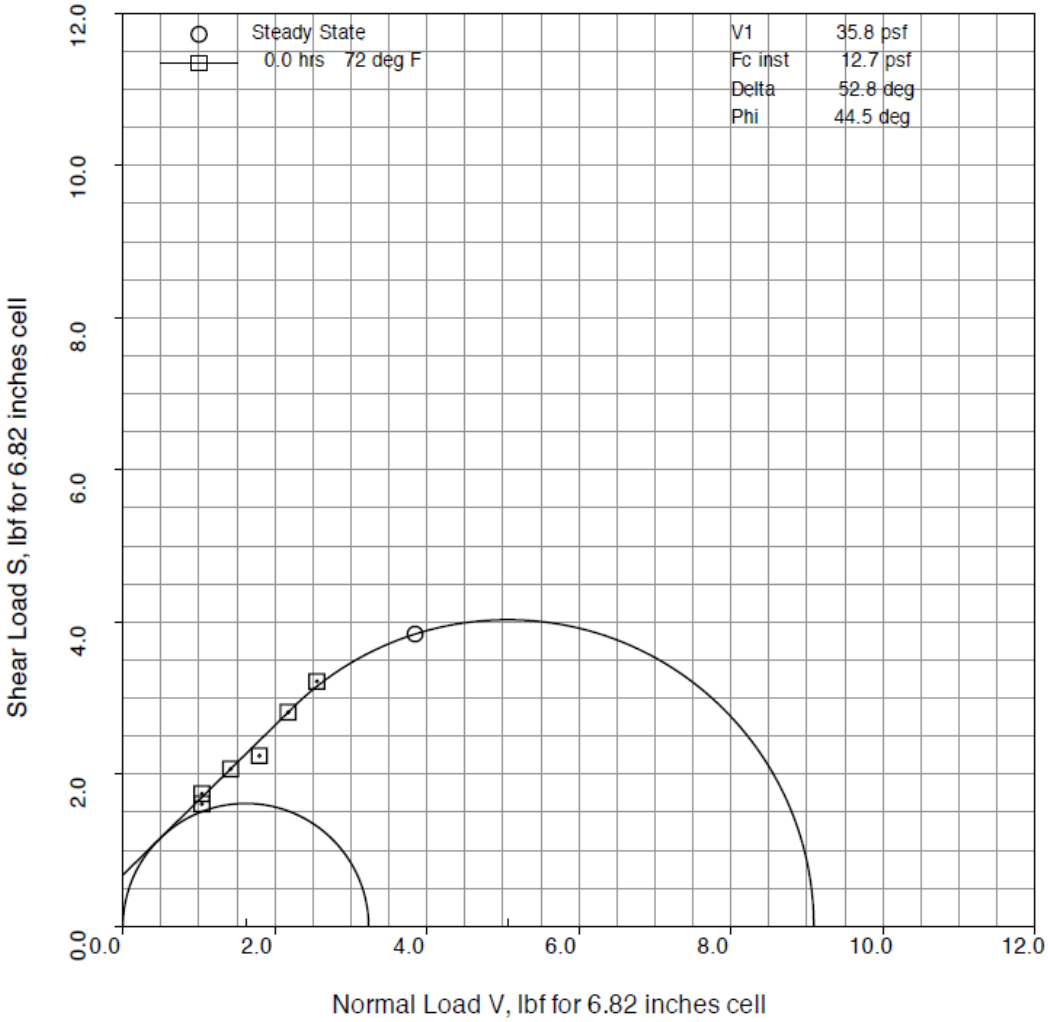
JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL: Shredded Waste 3 (20mm 20%mc)
PARTICLE SIZE: 20mm (As Rec'd)
MOISTURE % WT: As Rec'd

CREATE: 12/09/26
RUN: 12/10/03

JOB#: 11201
ID#: 29180

YIELD LOCUS

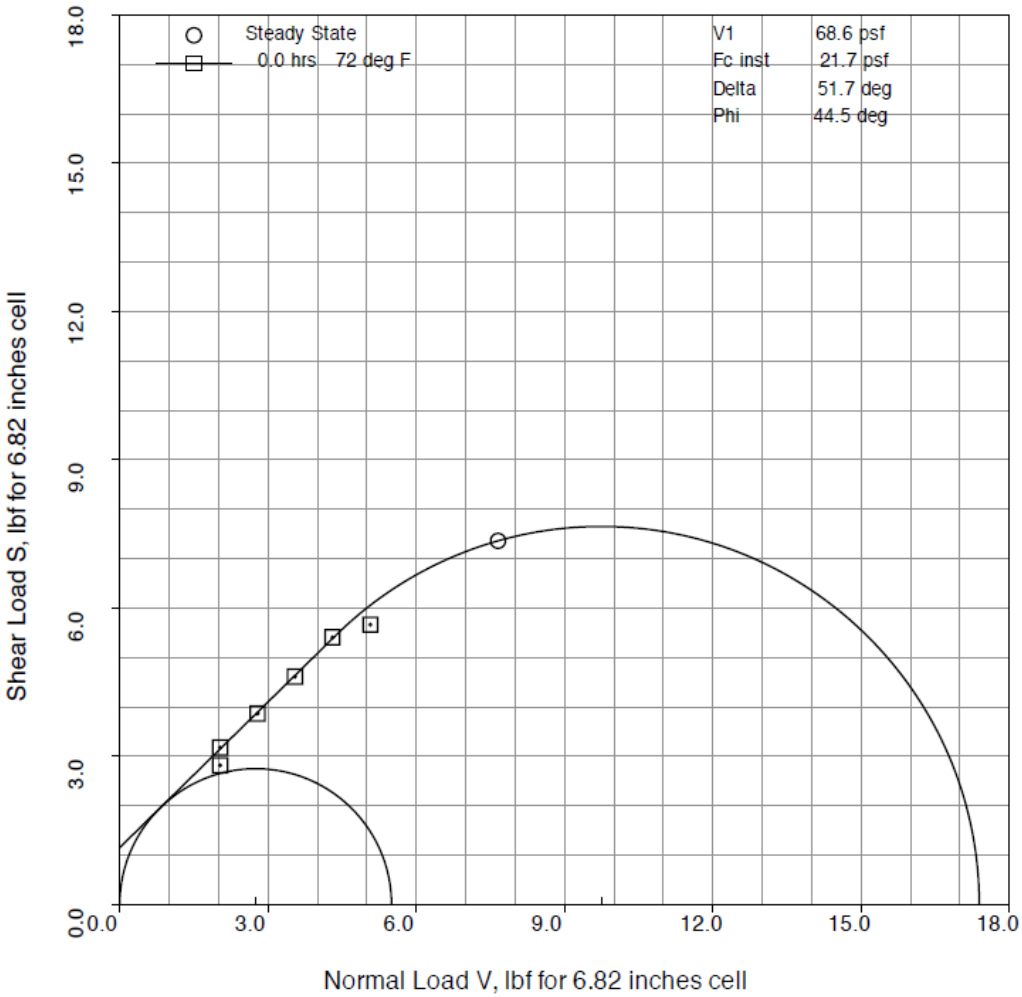


Plot 11

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL: Shredded Waste 3 (20mm 20%mc)
PARTICLE SIZE: 20mm (As Rec'd) CREATE: 12/09/26 JOB#: 11201
MOISTURE % WT: As Rec'd RUN: 12/10/03 ID#: 29180

YIELD LOCUS

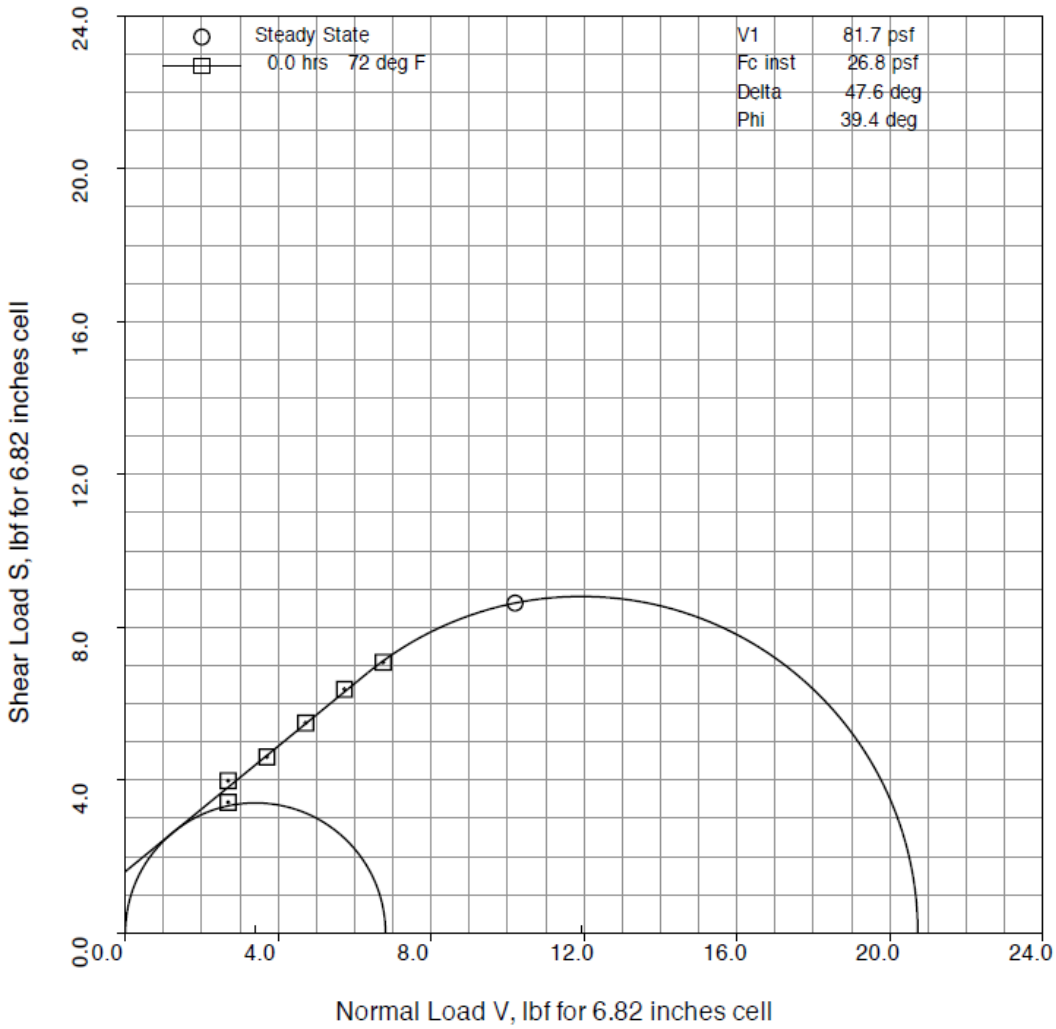


Plot 12

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL: Shredded Waste 3 (20mm 20%mc)
PARTICLE SIZE: 20mm (As Rec'd) CREATE: 12/09/26 JOB#: 11201
MOISTURE % WT: As Rec'd RUN: 12/10/03 ID#: 29180

YIELD LOCUS

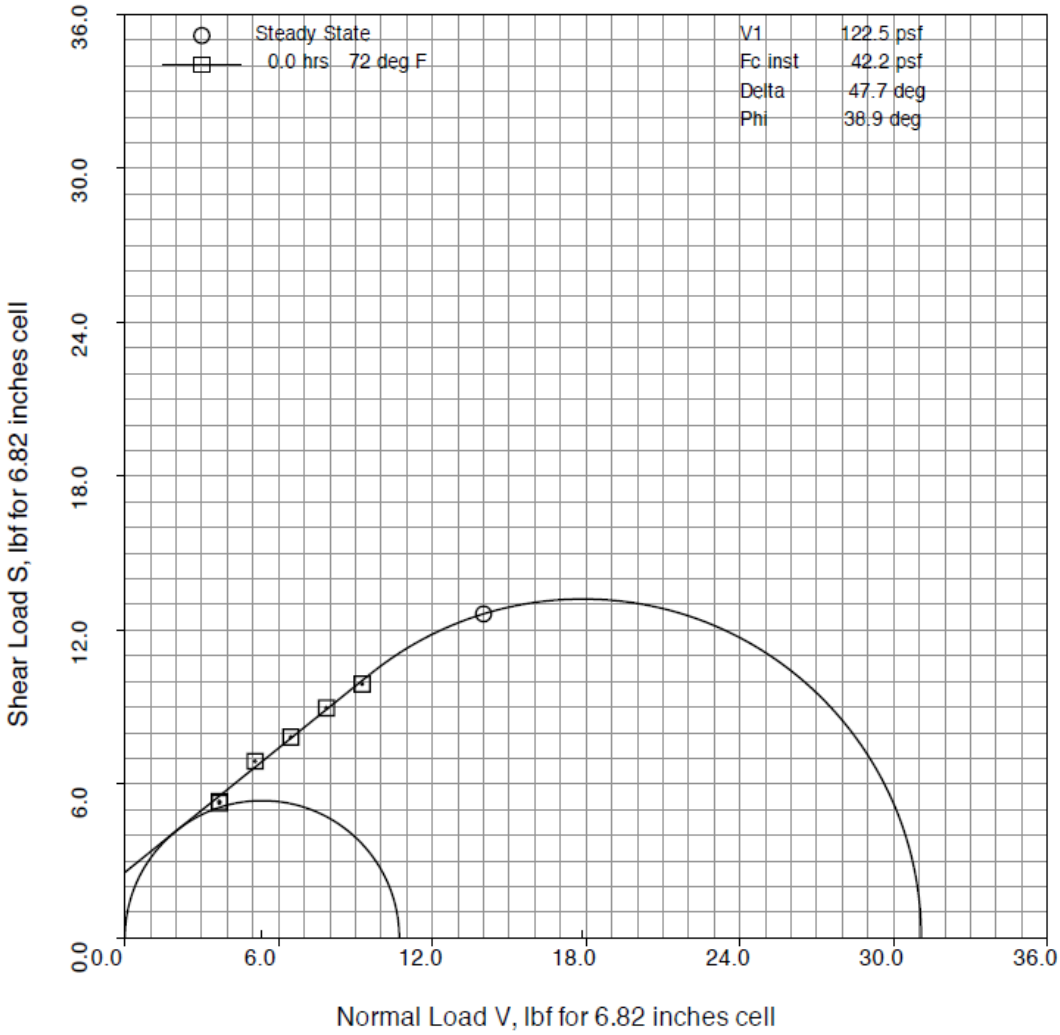


Plot 13

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL: Shredded Waste 3 (20mm 20%mc)
PARTICLE SIZE: 20mm (As Rec'd) CREATE: 12/09/26 JOB#: 11201
MOISTURE % WT: As Rec'd RUN: 12/10/03 ID#: 29180

YIELD LOCUS



Plot 14

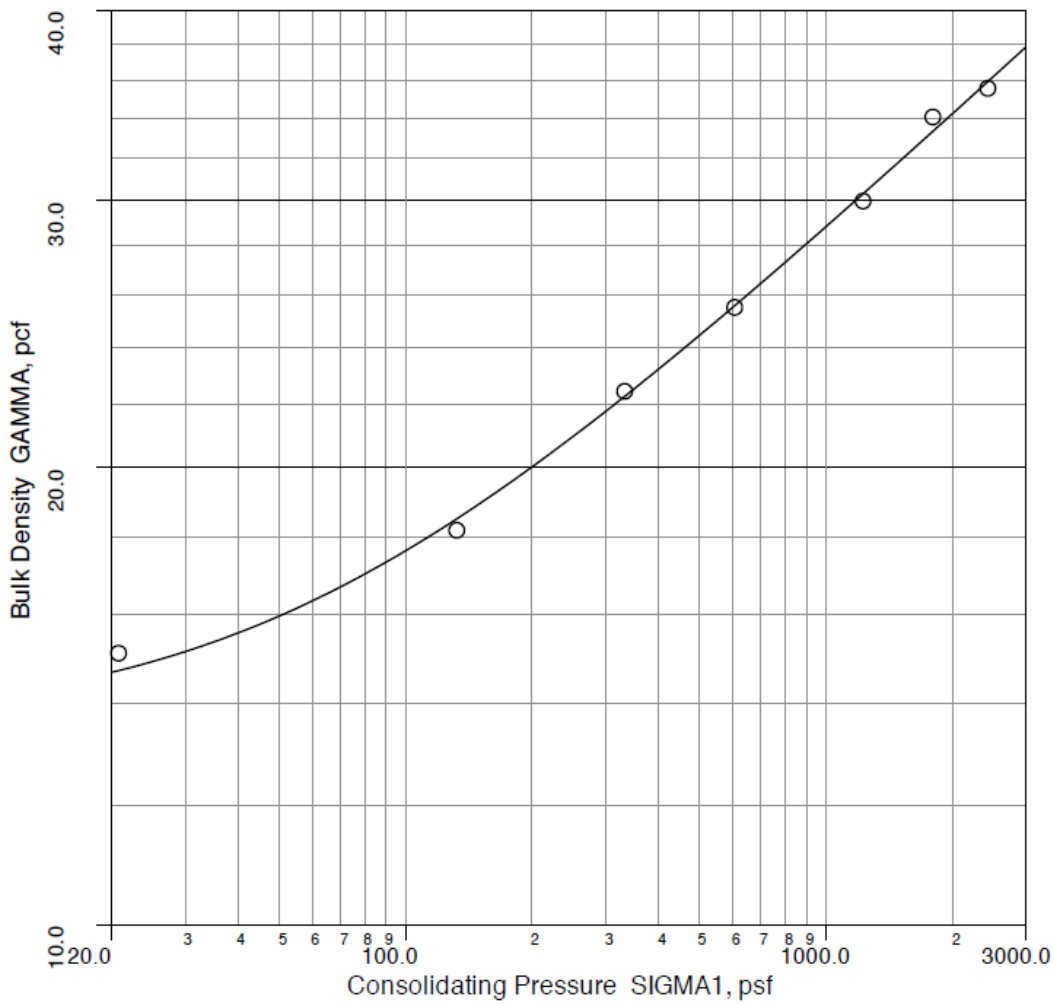
JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL: Shredded Waste 3 (20mm 20%mc)
PARTICLE SIZE: 20mm (As Rec'd)
MOISTURE % WT: As Rec'd
TEMPERATURE: 72 deg F

CREATE: 12/09/26
RUN: 12/10/03

JOB#: 11201
ID#: 29180

BULK DENSITY VS. CONSOLIDATING PRESSURE

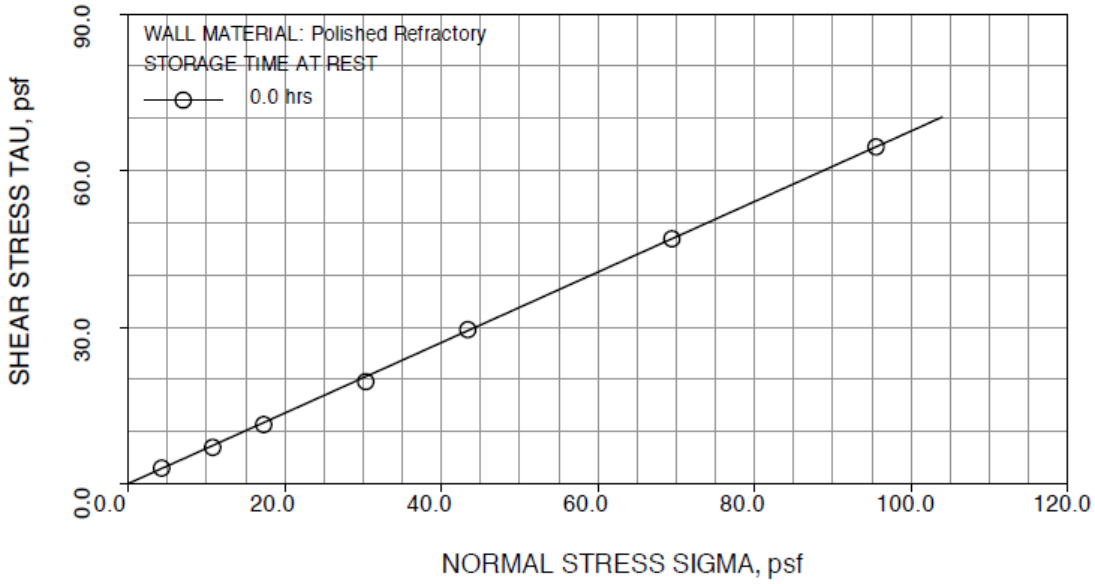


Plot 15

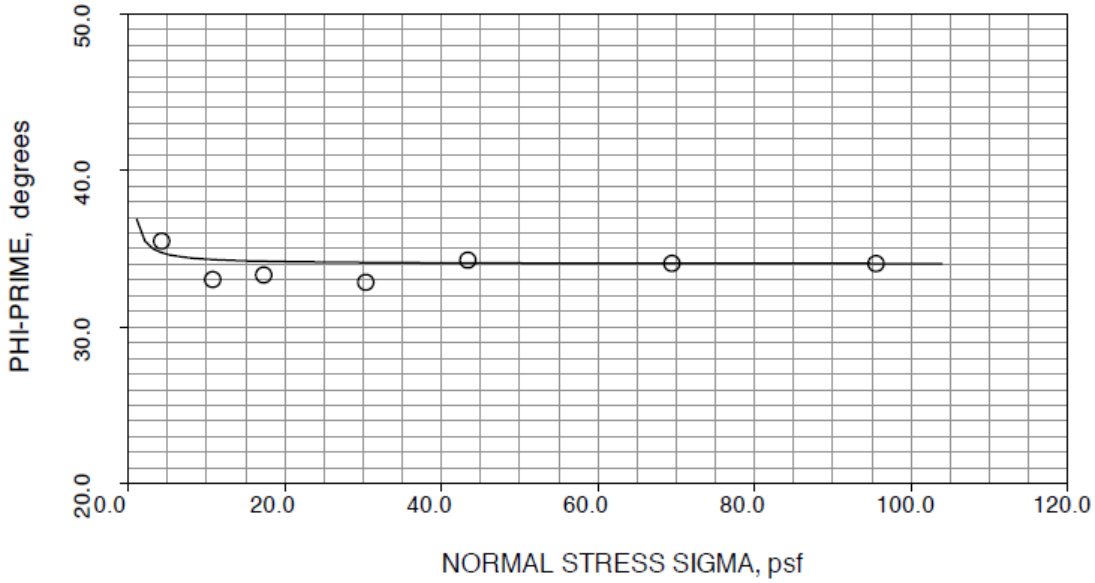
JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL: Shredded Waste 3 (20mm 20%mc)
PARTICLE SIZE: 20mm (As Rec'd) CREATE: 12/09/26 JOB#: 11201
MOISTURE % WT: As Rec'd RUN: 12/10/03 ID#: 29180
TEMPERATURE: 72 deg F

WALL YIELD LOCUS



WALL FRICTION ANGLE



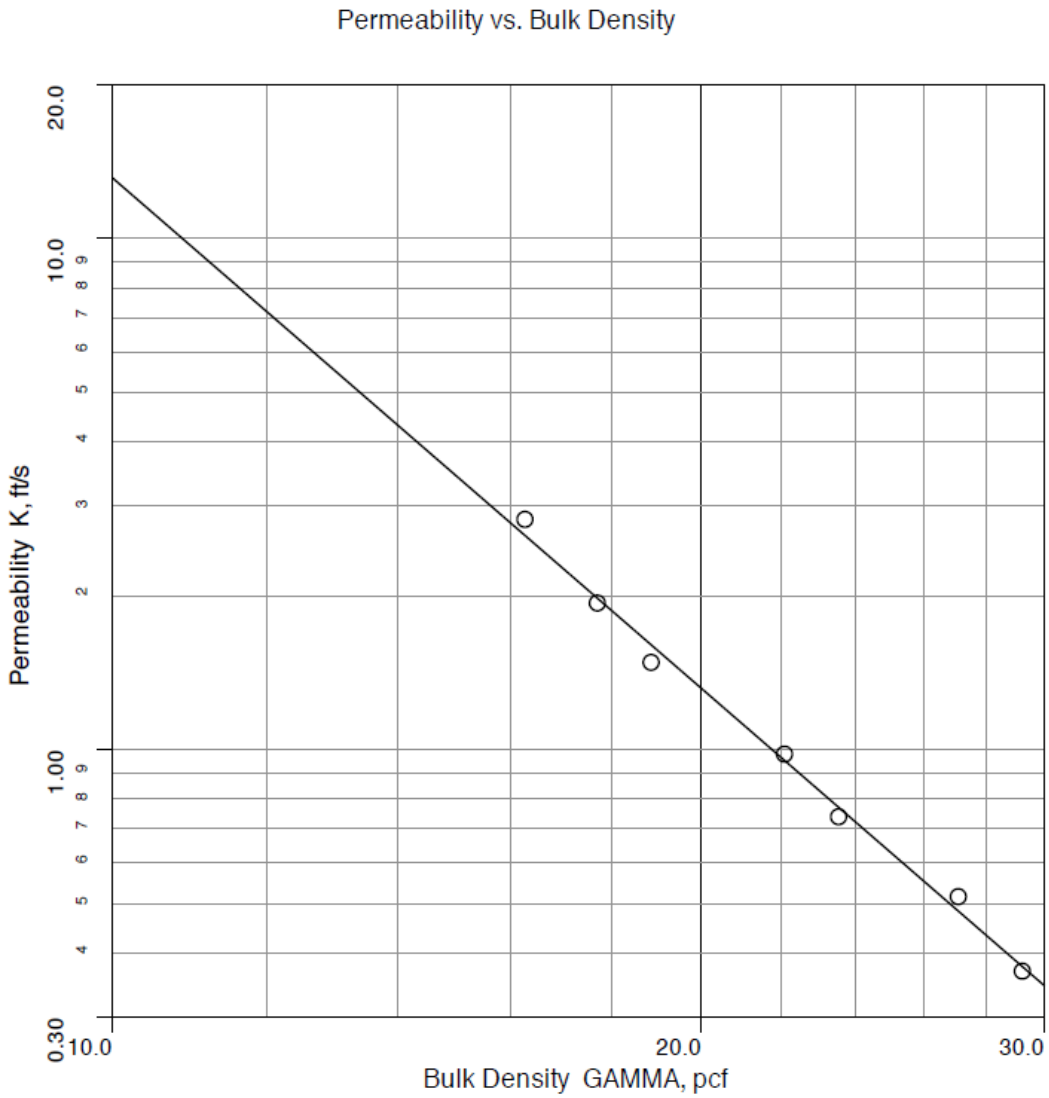
Plot 16

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL: Shredded Waste 3 (20mm 20%mc)
PARTICLE SIZE: 20mm (As Rec'd)
MOISTURE % WT: As Rec'd
TEMPERATURE: 68 deg F

CREATE: 12/09/26
RUN: 12/10/03

JOB#: 11201
ID#: 29180



Plot 17

JENIKE & JOHANSON

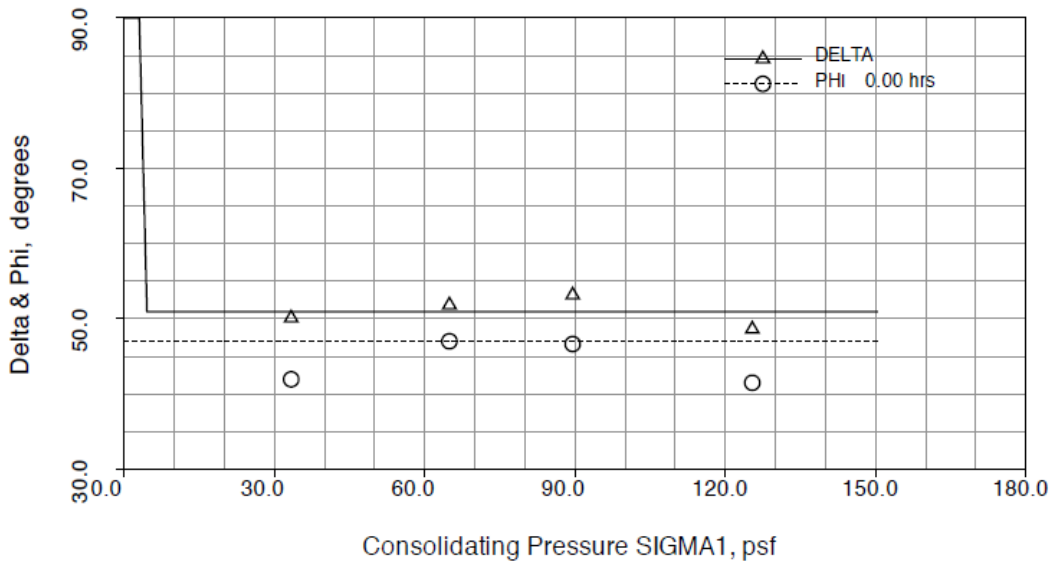
Bulk Solids: Science/Engineering/Design

BULK MATERIAL: Shredded Waste 4 (15mm 10%mc)

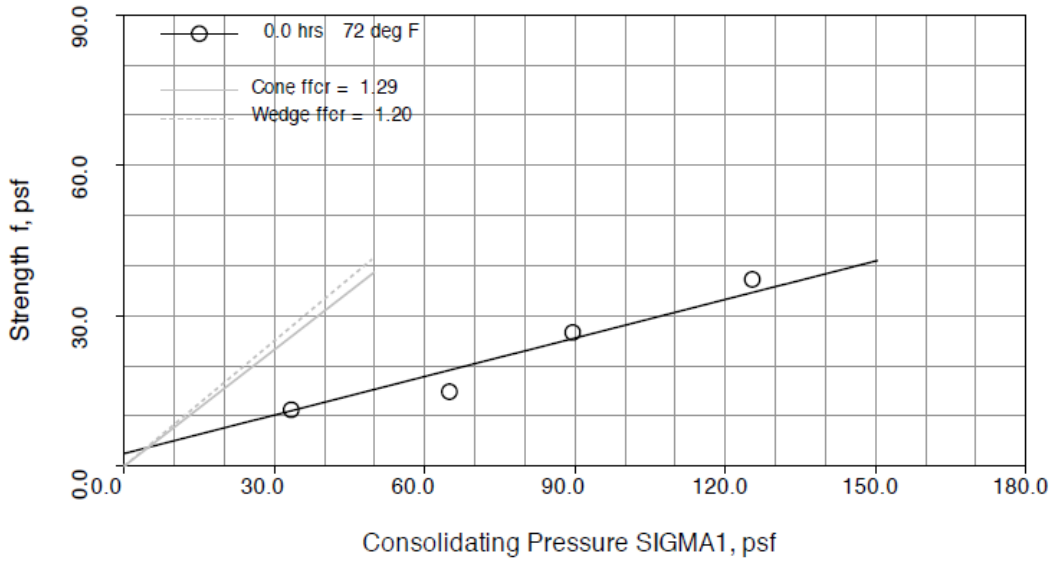
PARTICLE SIZE: 15mm (As Rec'd) CREATE: 12/09/26 JOB#: 11201

MOISTURE % WT: As Rec'd RUN: 12/10/03 ID#: 29181

DELTA & PHI RELATIONS



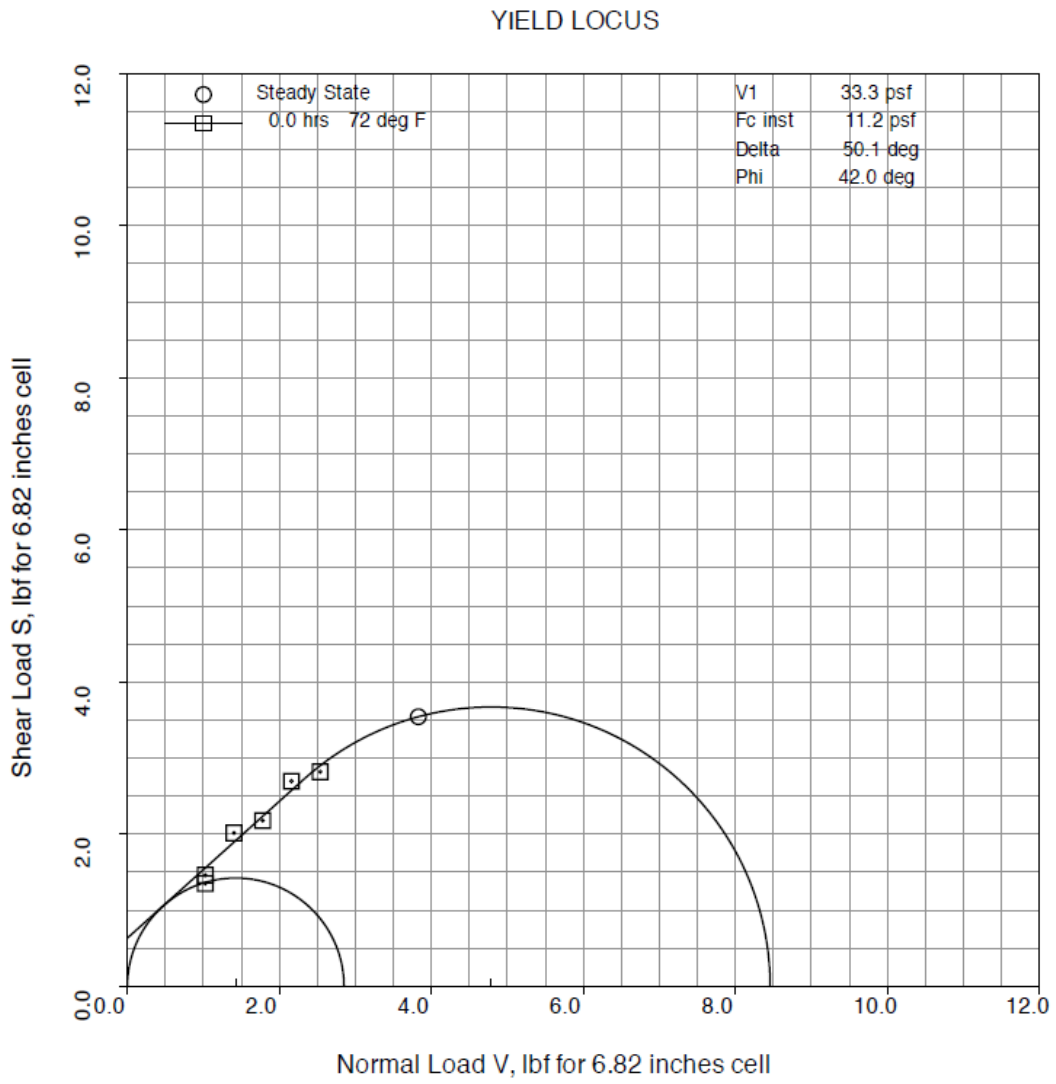
FLOW FUNCTION(S)



Plot 18

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

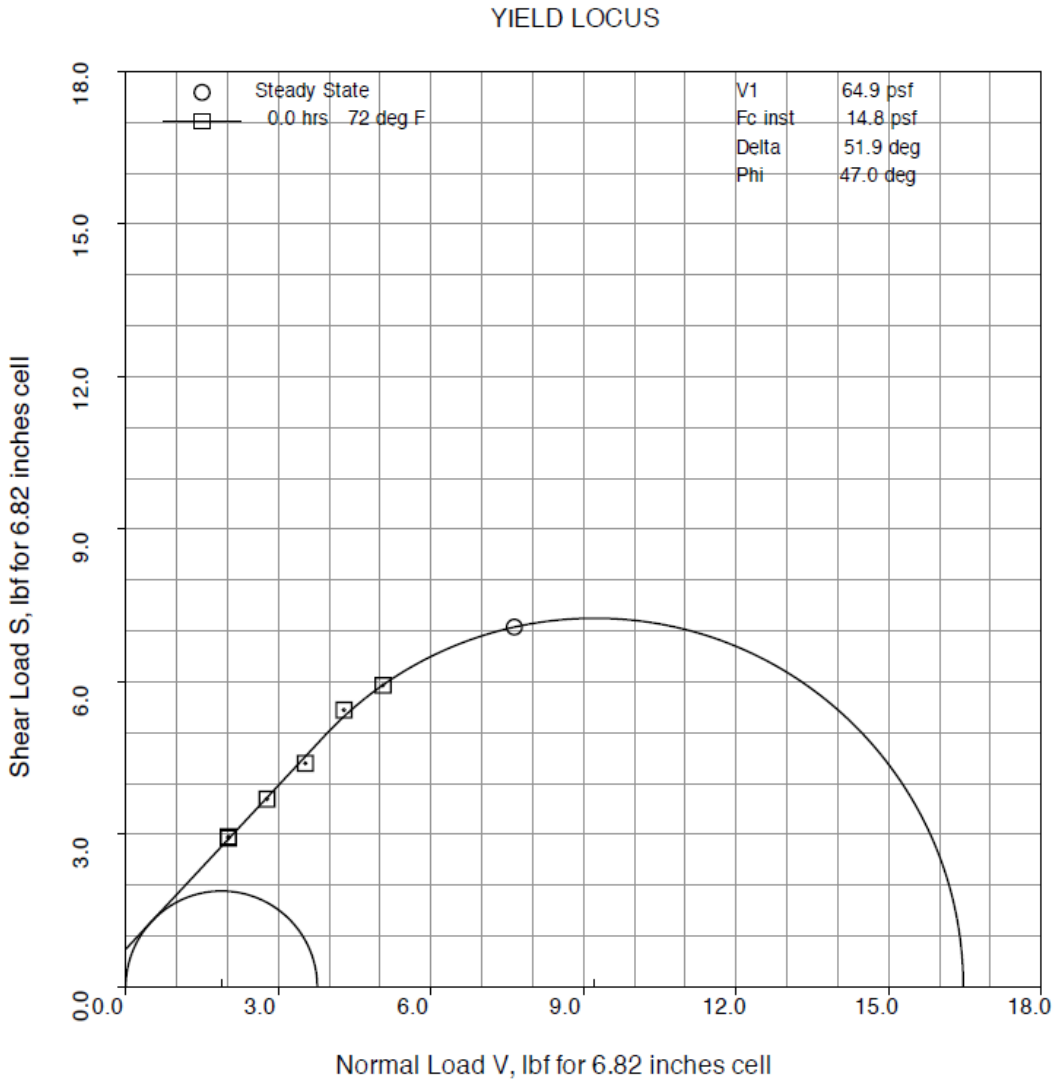
BULK MATERIAL: Shredded Waste 4 (15mm 10%mc)
PARTICLE SIZE: 15mm (As Rec'd) CREATE: 12/09/26 JOB#: 11201
MOISTURE % WT: As Rec'd RUN: 12/10/03 ID#: 29181



Plot 19

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL: Shredded Waste 4 (15mm 10%mc)
PARTICLE SIZE: 15mm (As Rec'd) CREATE: 12/09/26 JOB#: 11201
MOISTURE % WT: As Rec'd RUN: 12/10/03 ID#: 29181

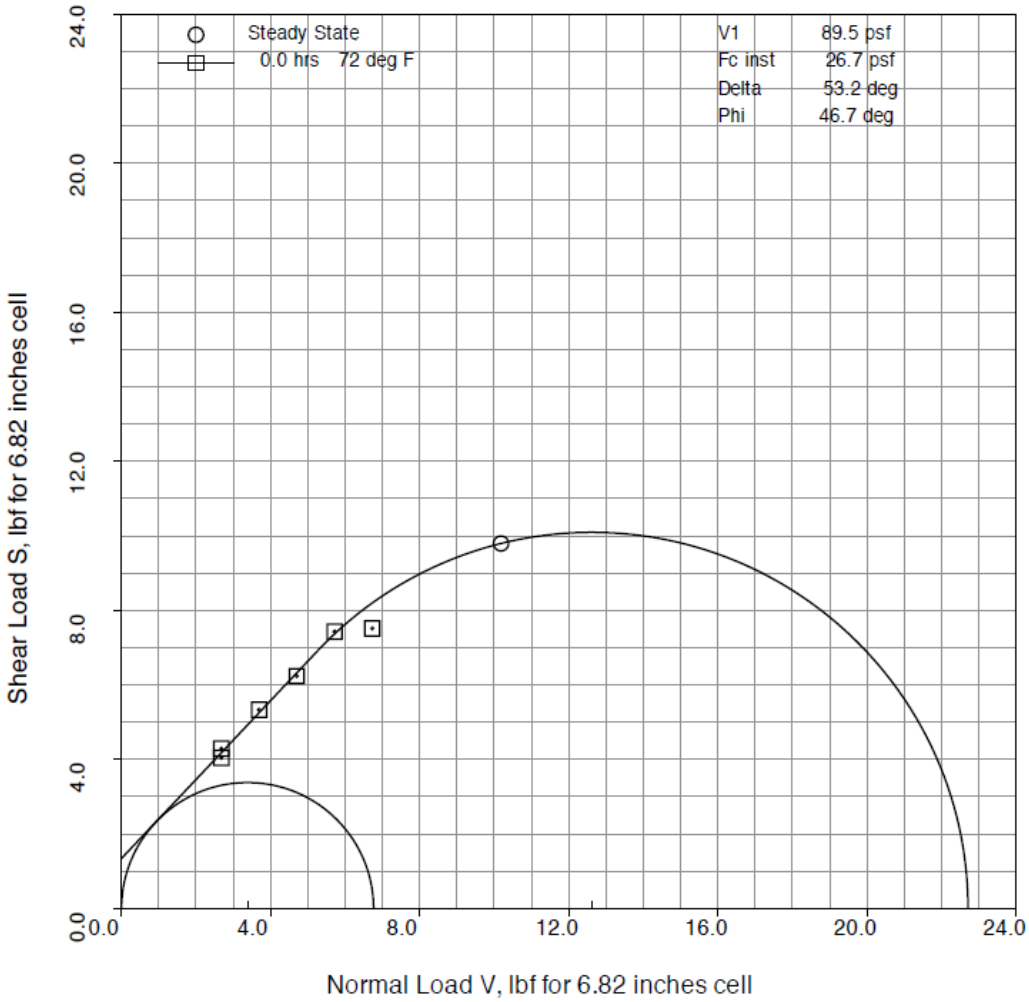


Plot 20

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL: Shredded Waste 4 (15mm 10%mc)
PARTICLE SIZE: 15mm (As Rec'd) CREATE: 12/09/26 JOB#: 11201
MOISTURE % WT: As Rec'd RUN: 12/10/03 ID#: 29181

YIELD LOCUS

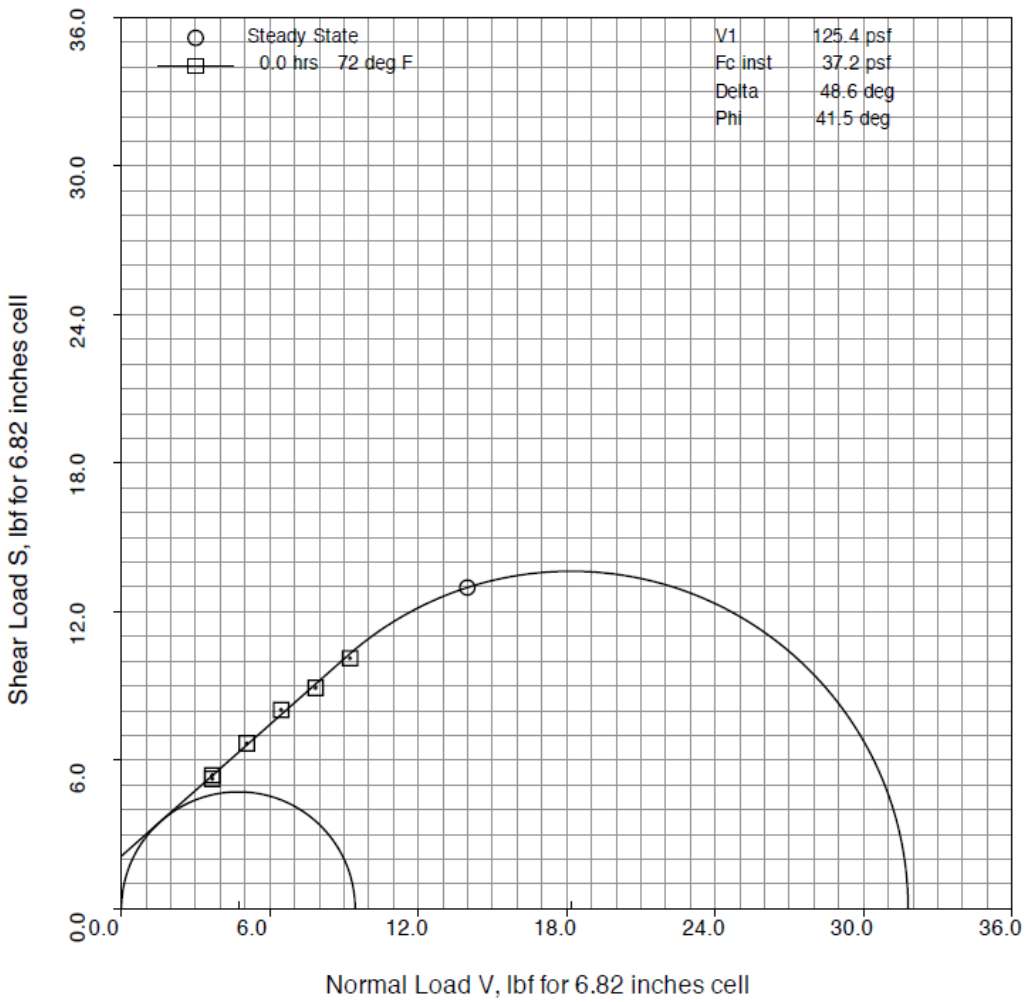


Plot 21

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL: Shredded Waste 4 (15mm 10%mc)
PARTICLE SIZE: 15mm (As Rec'd) CREATE: 12/09/26 JOB#: 11201
MOISTURE % WT: As Rec'd RUN: 12/10/03 ID#: 29181

YIELD LOCUS

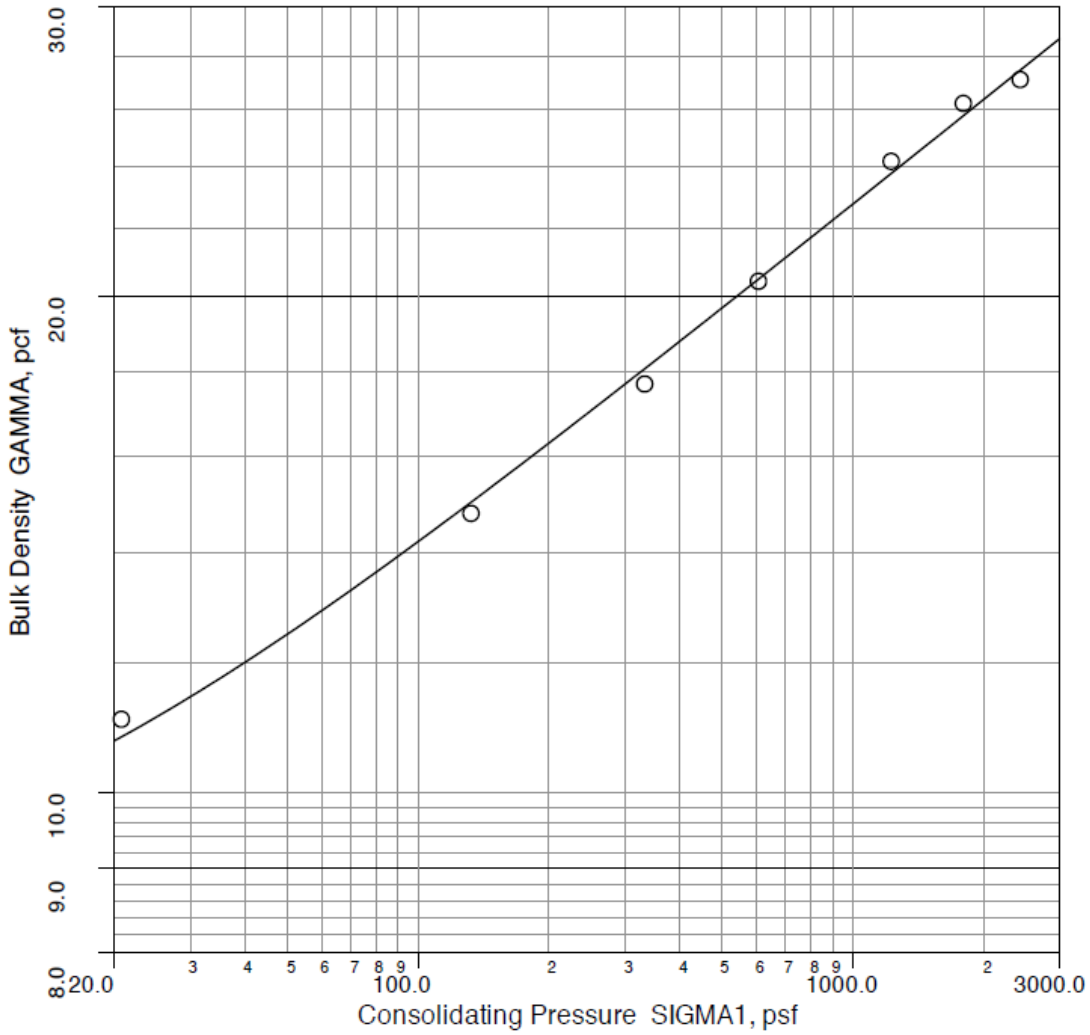


Plot 22

JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL: Shredded Waste 4 (15mm 10%mc)
PARTICLE SIZE: 15mm (As Rec'd) CREATE: 12/09/26 JOB#: 11201
MOISTURE % WT: As Rec'd RUN: 12/10/03 ID#: 29181
TEMPERATURE: 72 deg F

BULK DENSITY VS. CONSOLIDATING PRESSURE



Plot 23

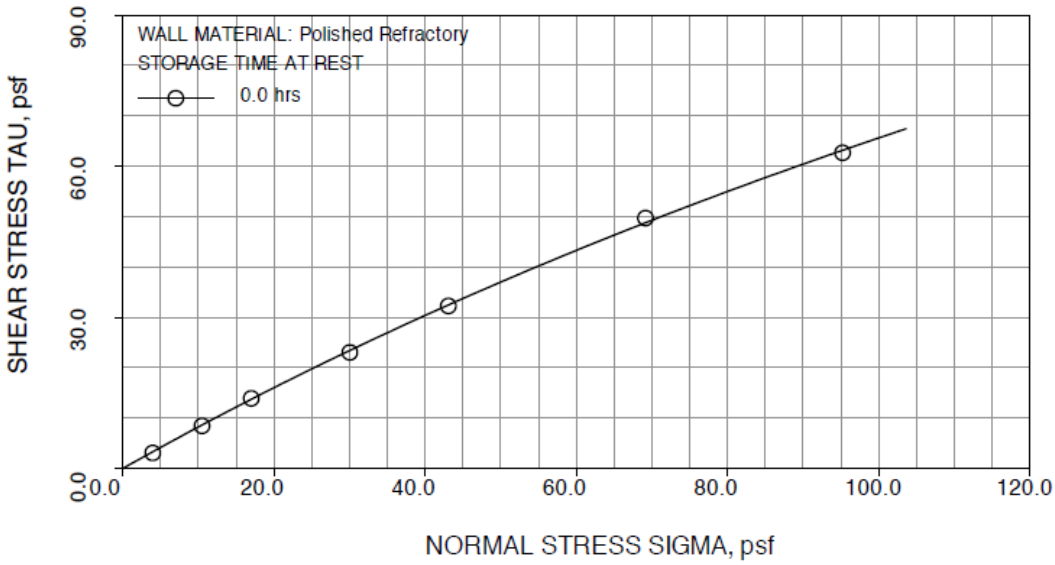
JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL: Shredded Waste 4 (15mm 10%mc)
PARTICLE SIZE: 15mm (As Rec'd)
MOISTURE % WT: As Rec'd
TEMPERATURE: 72 deg F

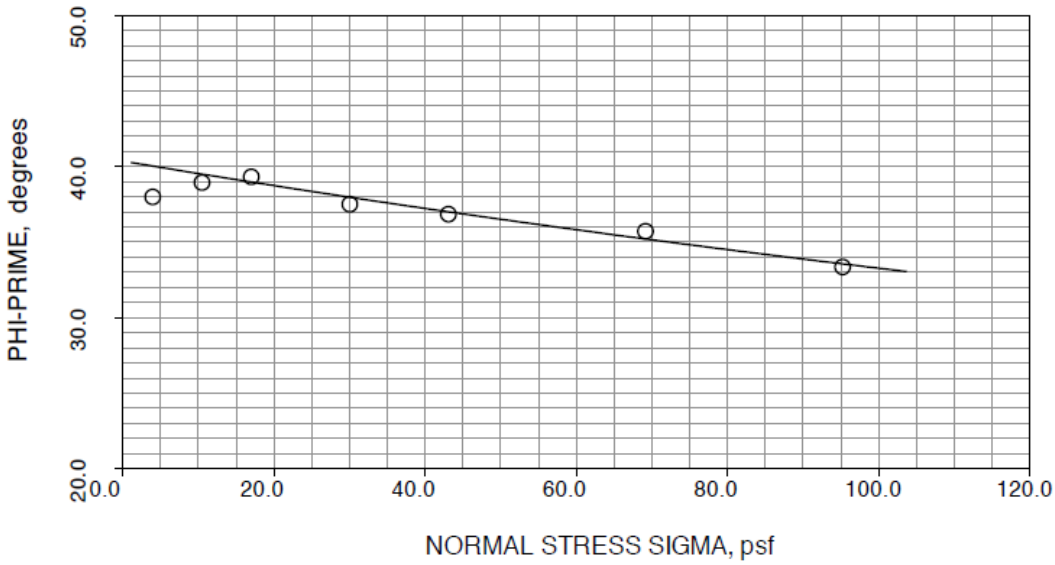
CREATE: 12/09/26
RUN: 12/10/03

JOB#: 11201
ID#: 29181

WALL YIELD LOCUS



WALL FRICTION ANGLE



Plot 24

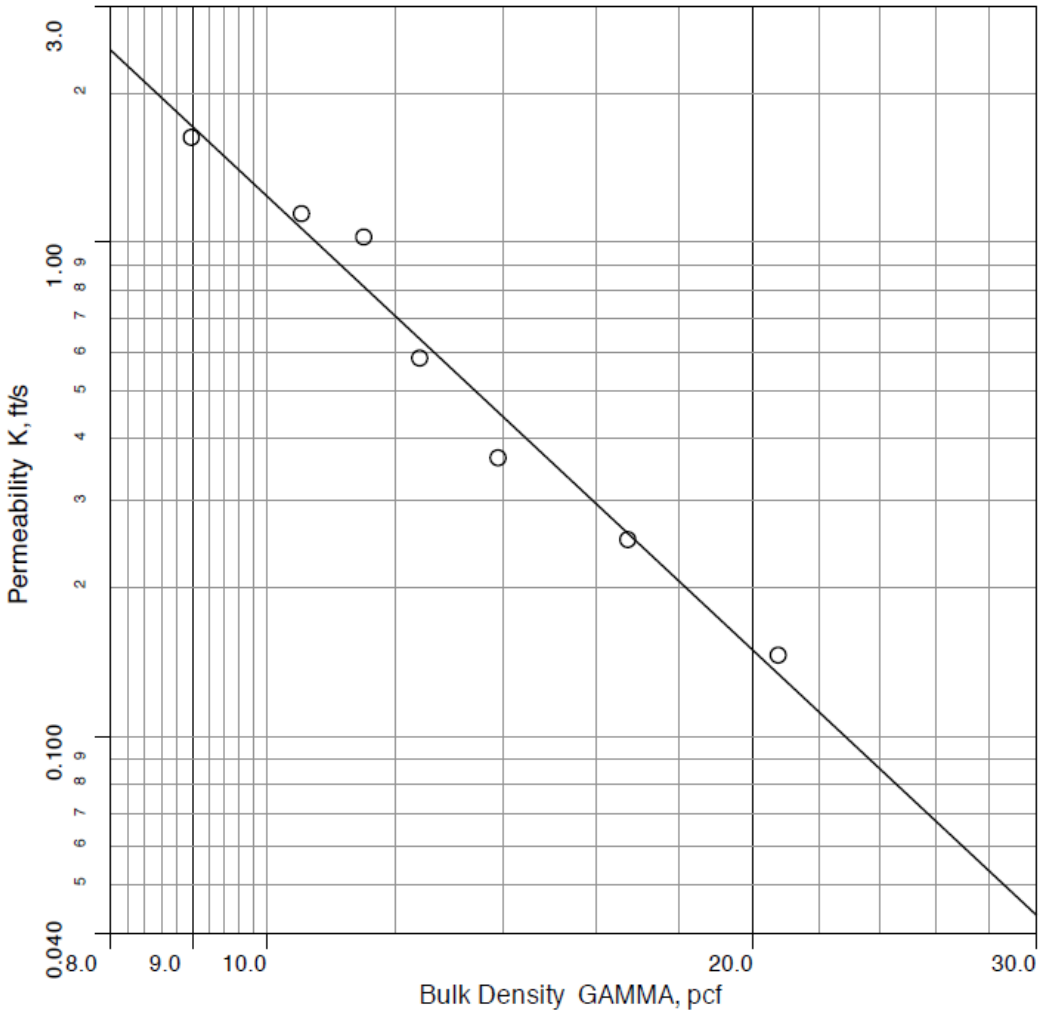
JENIKE & JOHANSON
Bulk Solids: Science/Engineering/Design

BULK MATERIAL: Shredded Waste 4 (15mm 10%mc)
PARTICLE SIZE: 15mm (As Rec'd)
MOISTURE % WT: As Rec'd
TEMPERATURE: 68 deg F

CREATE: 12/09/26
RUN: 12/10/03

JOB#: 11201
ID#: 29181

Permeability vs. Bulk Density



Plot 25

A2 Char Ash Material Flow Characterization Data

JENIKE & JOHANSON

SUMMARY OF TESTS PERFORMED

This report presents various flow property test results as indicated for the following material(s) :

BULK MATERIAL	MATERIAL ID #	DESCRIPTION	PARTICLE SIZE	MOISTURE CONTENT
1	29323	Edwards Char Ash	As Rec'd	As Rec'd

BULK MATERIAL	TIME hr	TEMPERATURE deg C	SIEVE ANALYSIS	BIN DIM	BULK DENSITY	HOPPER ANGLES	CHUTE ANGLES	FLOW RATE	OTHER
1	0.0	850		X	X	X		X	X

JENIKE & JOHANSON

BULK MATERIAL 1: Edwards Char Ash

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

SECTION I. BIN DIMENSIONS FOR DEPENDABLE FLOW

Storage Time at Rest 0.0 hrs
Temperature 850 deg C

PART A. BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

P-Factor	BC feet	BP feet
1.00	0.2	0.1
1.25	0.2	0.1
1.50	0.3	0.1
2.00	0.3	0.1

Funnel Flow Dimensions

P-Factor	BF (feet)	EH=	0.5	1.0	2.5	5	10	13 feet
			Critical Rathole Diameters, DF (feet)					
1.00	0.1		0.7	1.0	2.1	3.8	7	10
1.25	0.1							
1.50	0.2							
2.00	0.2							

TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectangular outlet in a funnel flow bin
EH = effective consolidating head

JENIKE & JOHANSON

BULK MATERIAL 1: Edwards Char Ash

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

SECTION II. SOLIDS DENSITY

TEMPERATURE 22 deg C

BULK DENSITY
The bulk density, GAMMA, is a function of the major consolidating pressure, SIGMA1, expressed in terms of effective head, EH.

EH (feet)	0.5	1.0	2.5	5.0	10.0	20.0	40.0	80.0
SIGMA1 (psf)	13.	26.	67.	137.	282.	580.	1193.	2455.
GAMMA (pcf)	25.1	25.8	26.7	27.4	28.2	29.0	29.8	30.7

COMPRESSIBILITY PARAMETERS

Bulk density, GAMMA, is a function of the major consolidating pressure SIGMA1, as follows:

$$GAMMA = GAMMAM\ (SIGMA1/SIGMAM + 1)^{BETAM}$$

For GAMMA between 25.6 and 30.9 pcf

Minimum bulk density GAMMAM = 22.9 pcf

SIGMAM = 1.27 psf

BETAM = 0.03884

JENIKE & JOHANSON

BULK MATERIAL 1: Edwards Char Ash

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

SECTION III. MAXIMUM HOPPER ANGLES FOR MASS FLOW

WALL MATERIAL: Polished Refractory
STORAGE TIME AT REST 0.0 hrs
TEMPERATURE 850 deg C

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)	1.62	4.00	8.00	16.00	37.09
Width of Oval (feet)	0.92	2.20	4.30	8.52	19.63
SIGMA (psf)	13.1	36.2	79.	170.	420.
SIGMA1 (psf)	24.8	65.5	138.	294.	716.
Wall Friction Angle PHI-PRIME (deg)	46.	43.	41.	39.	37.
Hopper Angles THETA-P (deg)	8.*	9.*	11.*	12.*	13.*
THETA-C (deg)	0.*	0.*	1.*	2.*	2.*

* Flow along walls is questionable.

JENIKE & JOHANSON

BULK MATERIAL 1: Edwards Char Ash

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

SECTION IV. CRITICAL STEADY SOLIDS FLOW RATES IN AIR

TEMPERATURE 850.0 deg C

CONICAL MASS FLOW HOPPER

Flow rate expressed in units of tons/hr.

BC	EH = 2.5 feet	5.0 feet	10.0 feet	20.0 feet	40.0 feet
0.50 feet	0.04	0.04	0.03	0.03	0.02
0.75 feet	0.12	0.10	0.09	0.08	0.07
1.00 feet	0.23	0.20	0.17	0.15	0.13
2.00 feet	1.0	0.88	0.77	0.68	0.61
4.00 feet	4.5	3.7	3.2	2.8	2.5
8.00 feet	18.	15.	13.	11.	10.

TRANSITION MASS FLOW HOPPER

Flow rate expressed in units of tons/hr per feet length of outlet.

BP	EH = 2.5 feet	5.0 feet	10.0 feet	20.0 feet	40.0 feet
0.25 feet	0.05	0.04	0.03	0.03	0.03
0.50 feet	0.14	0.12	0.10	0.09	0.08
0.75 feet	0.23	0.20	0.17	0.15	0.13
1.00 feet	0.32	0.27	0.23	0.22	0.18
2.00 feet	0.70	0.59	0.50	0.45	0.40
4.00 feet	1.4	1.2	1.0	0.94	0.83
8.00 feet	2.9	2.5	2.1	1.8	1.6

TERMS

BC = diameter of circular outlet
BP = width of slotted outlet
EH = effective consolidating head

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BULK MATERIAL 1: Edwards Char Ash

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

SECTION V. AIR PERMEABILITY TEST RESULTS

Temperature of test 20 deg C

K, the AIR permeability factor of the solid is defined from Darcy's law in the following form:

$$K = -u\ (GAMMA)\ /\ (dp/dx)$$

where:

u = superficial AIR velocity through the bed of solids

dp/dx = AIR pressure gradient across the bed

GAMMA = bulk density of the solid in the bed

K is a function of the bulk density of the solid

$$K = K0\ (GAMMA\ /\ GAMMA0)^{-a}$$

At room temperature, for GAMMA between 25.1 and 32.4 pcf:

K0 = 0.002084 ft/s

GAMMA0 = 25.1 pcf

a = 5.65

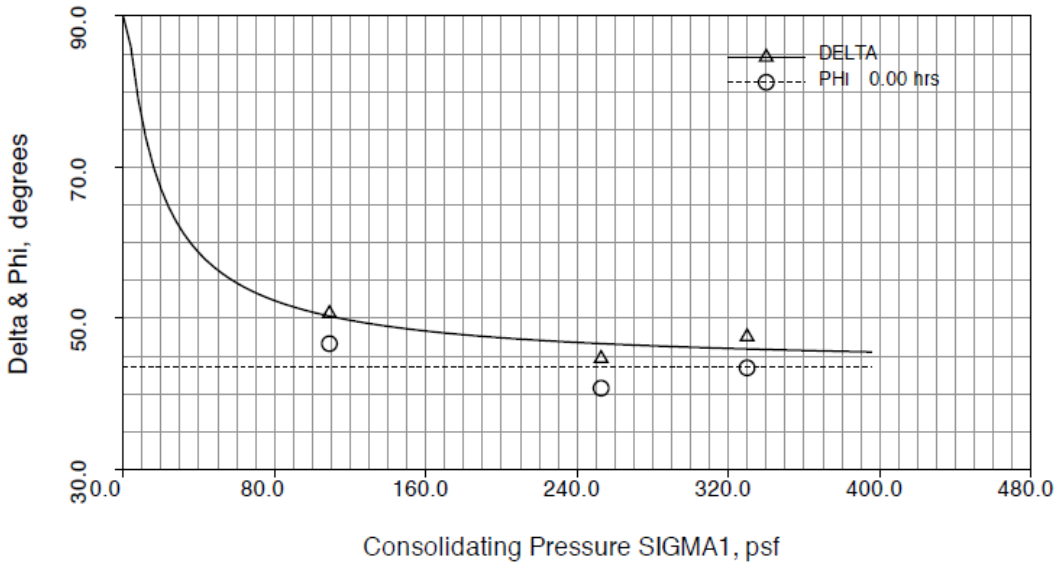
JENIKE & JOHANSON

BULK MATERIAL: Edwards Char Ash
PARTICLE SIZE: As Rec'd
MOISTURE % WT: As Rec'd

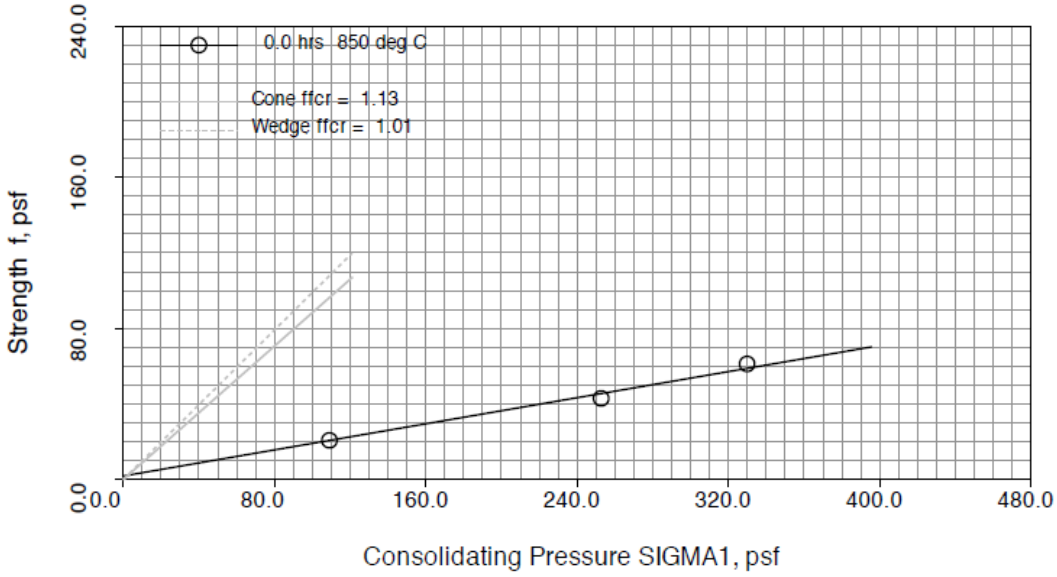
CREATE: 12/11/19
RUN: 12/12/02

JOB#: 11201
ID#: 29323

DELTA & PHI RELATIONS



FLOW FUNCTION(S)



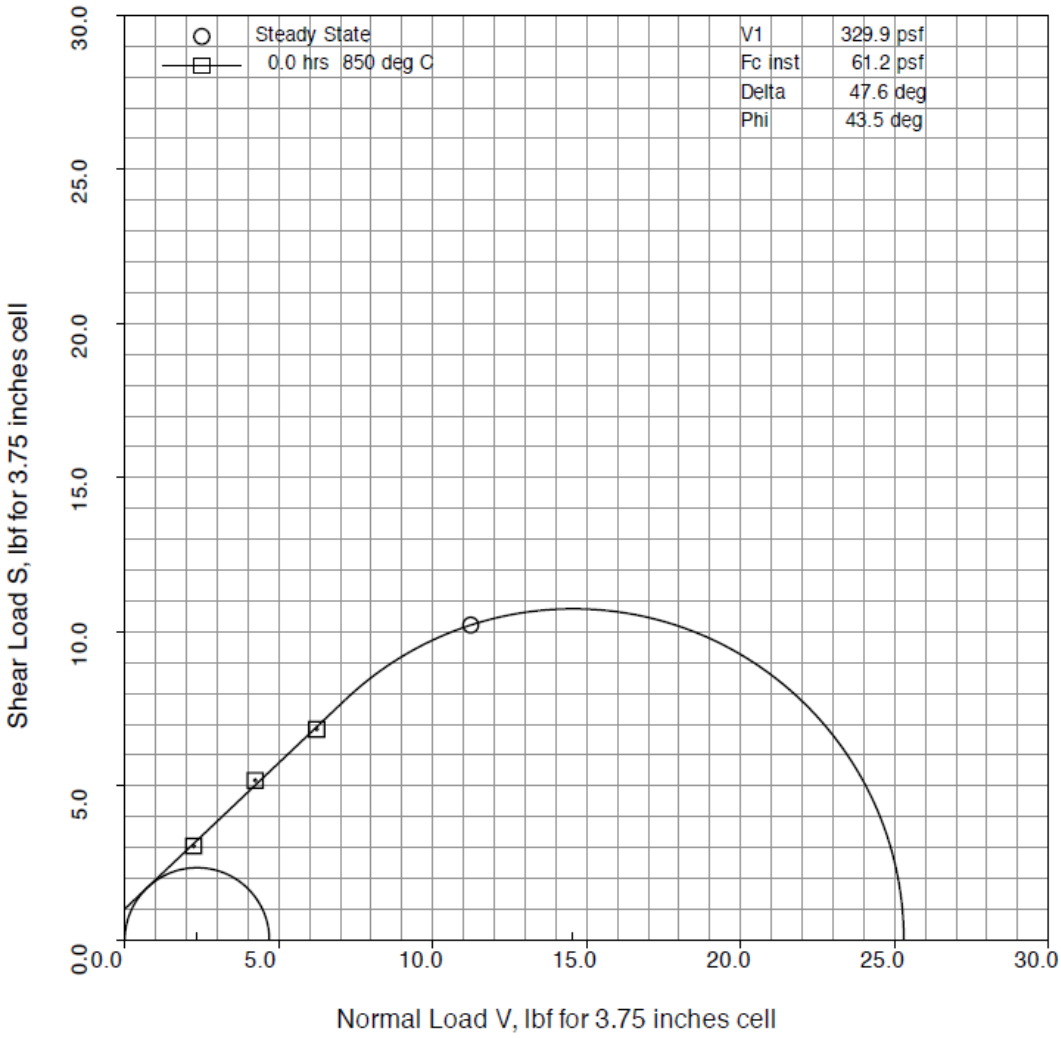
Plot 1

JENIKE & JOHANSON

BULK MATERIAL: Edwards Char Ash

PARTICLE SIZE: As Rec'd	CREATE:	12/11/19	JOB#: 11201
MOISTURE % WT: As Rec'd	RUN:	12/12/02	ID#: 29323

YIELD LOCUS



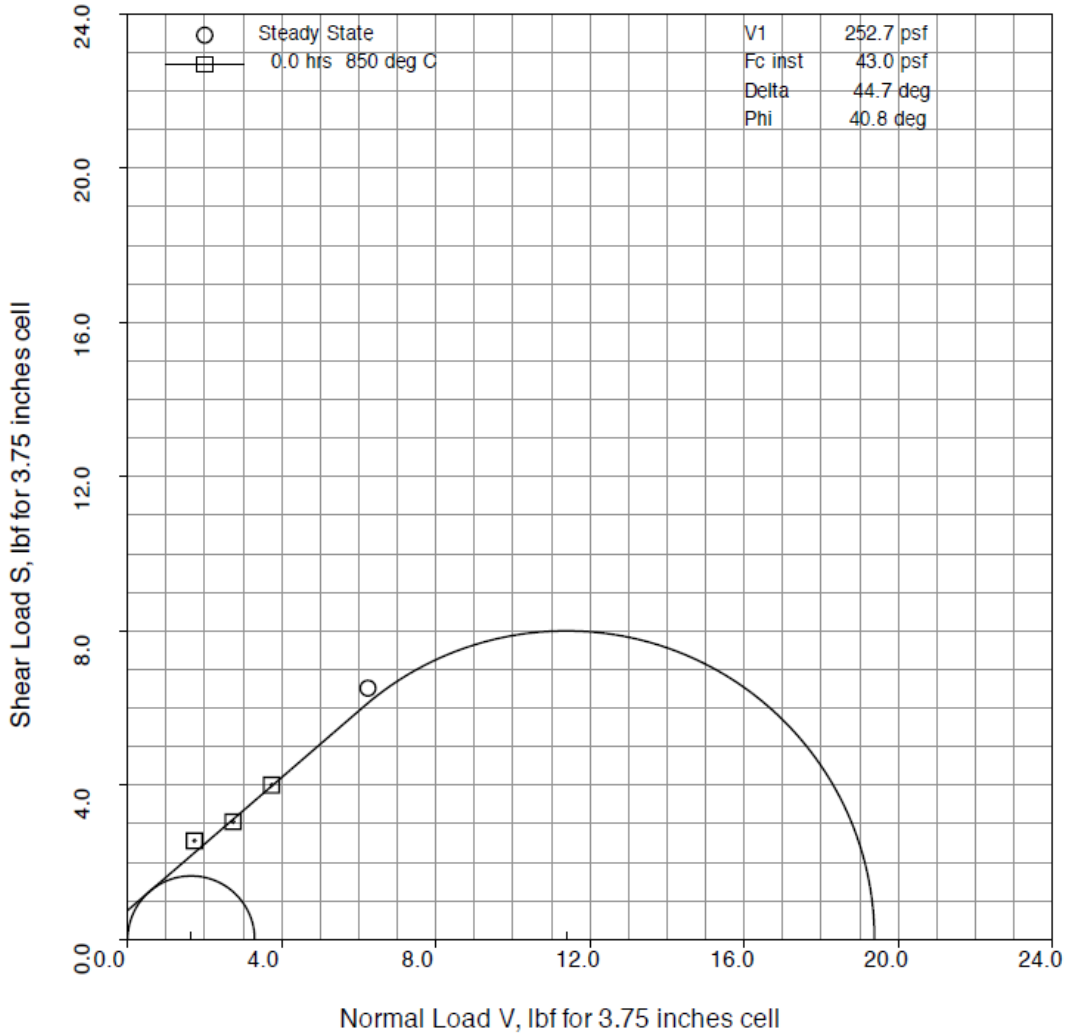
Plot 2

JENIKE & JOHANSON

BULK MATERIAL: Edwards Char Ash

PARTICLE SIZE: As Rec'd	CREATE:	12/11/19	JOB#: 11201
MOISTURE % WT: As Rec'd	RUN:	12/12/02	ID#: 29323

YIELD LOCUS

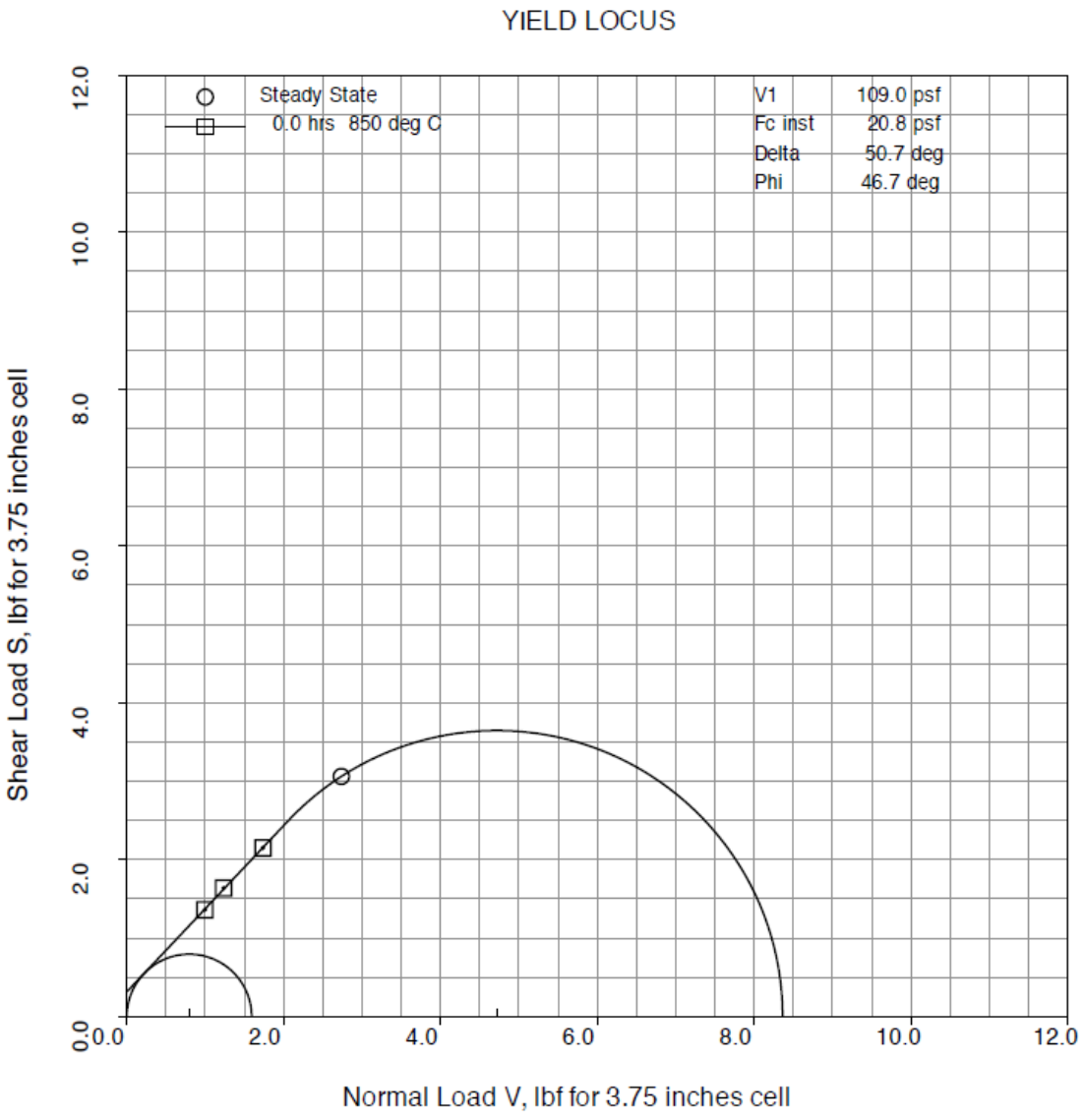


Plot 3

JENIKE & JOHANSON

BULK MATERIAL: Edwards Char Ash

PARTICLE SIZE: As Rec'd	CREATE:	12/11/19	JOB#: 11201
MOISTURE % WT: As Rec'd	RUN:	12/12/02	ID#: 29323



Plot 4

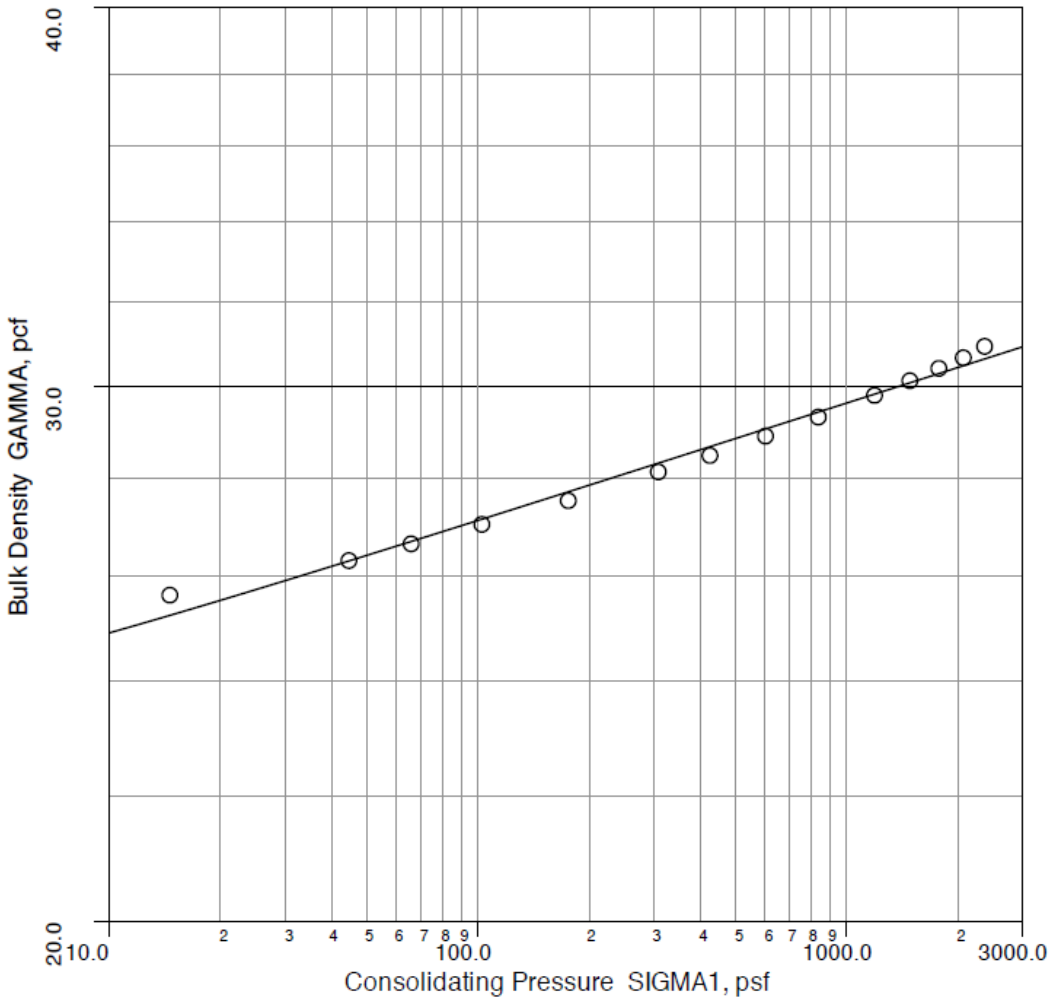
JENIKE & JOHANSON

BULK MATERIAL: Edwards Char Ash
PARTICLE SIZE: As Rec'd
MOISTURE % WT: As Rec'd
TEMPERATURE: 22 deg C

CREATE: 12/11/19
RUN: 12/12/02

JOB#: 11201
ID#: 29323

BULK DENSITY VS. CONSOLIDATING PRESSURE



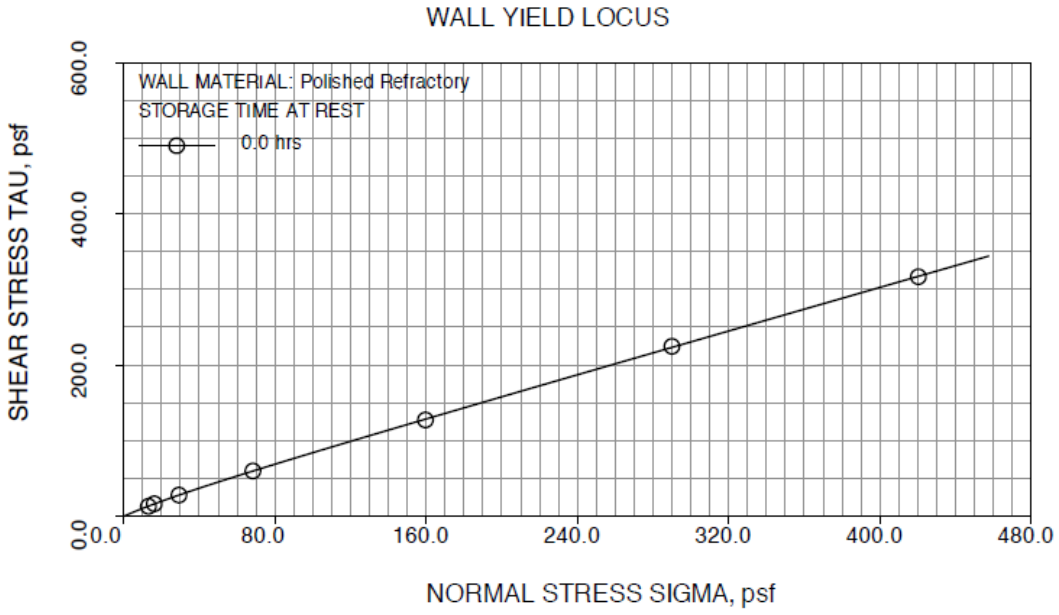
Plot 5

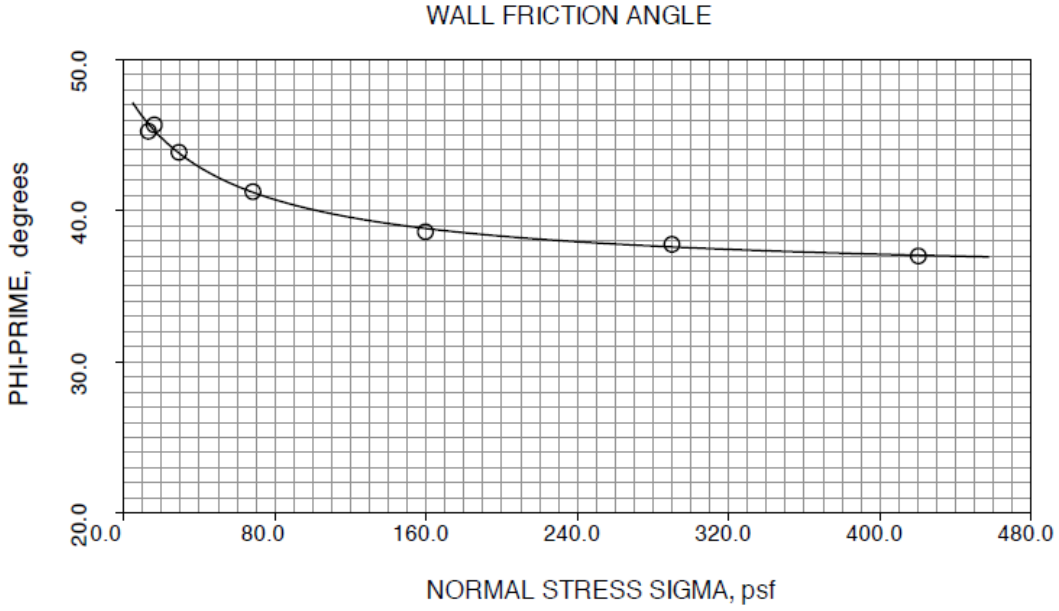
JENIKE & JOHANSON

BULK MATERIAL: Edwards Char Ash
PARTICLE SIZE: As Rec'd
MOISTURE % WT: As Rec'd
TEMPERATURE: 850 deg C

CREATE: 12/11/19
RUN: 12/12/02

JOB#: 11201
ID#: 29323





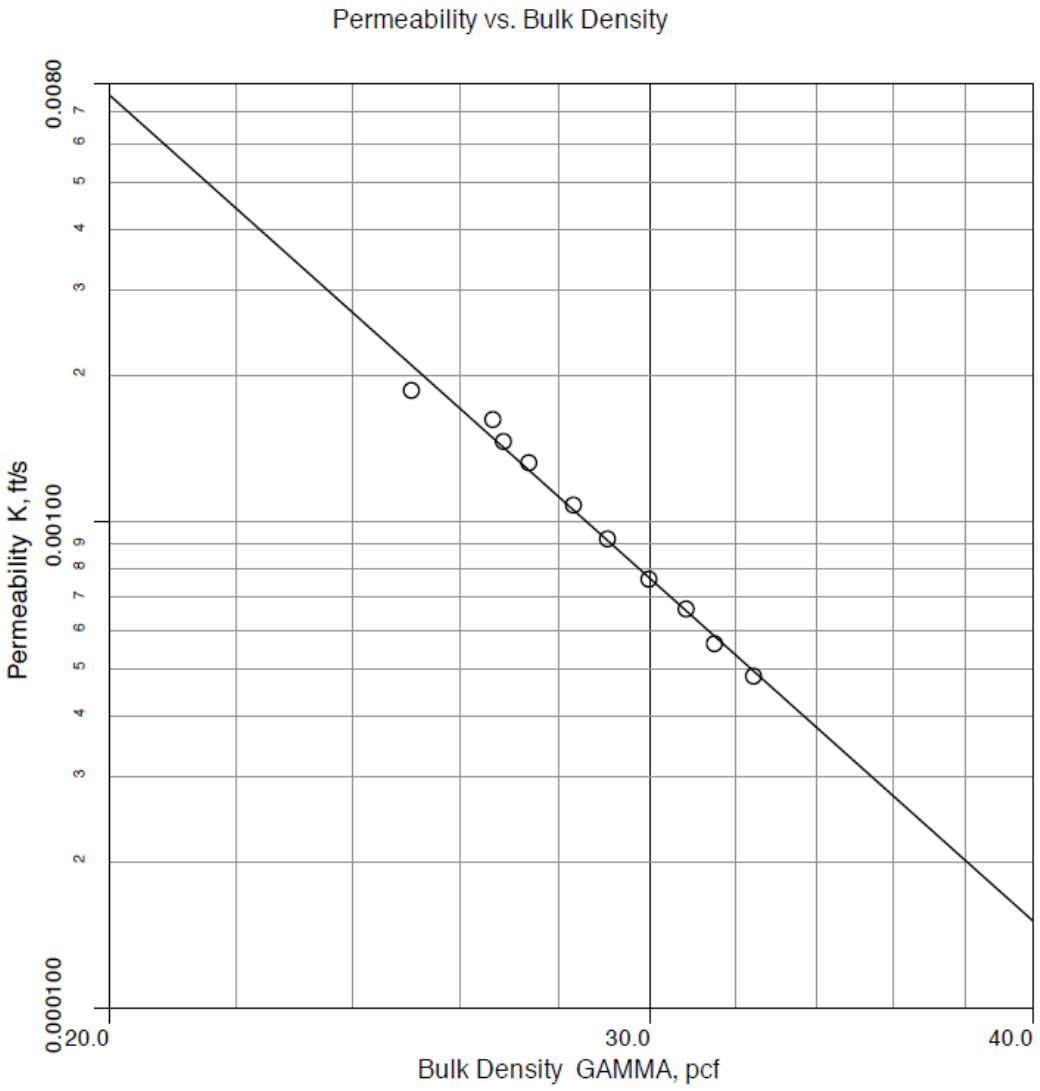
Plot 6

JENIKE & JOHANSON

BULK MATERIAL: Edwards Char Ash
PARTICLE SIZE: As Rec'd
MOISTURE % WT: As Rec'd
TEMPERATURE: 20 deg C

CREATE: 12/11/19
RUN: 12/12/02

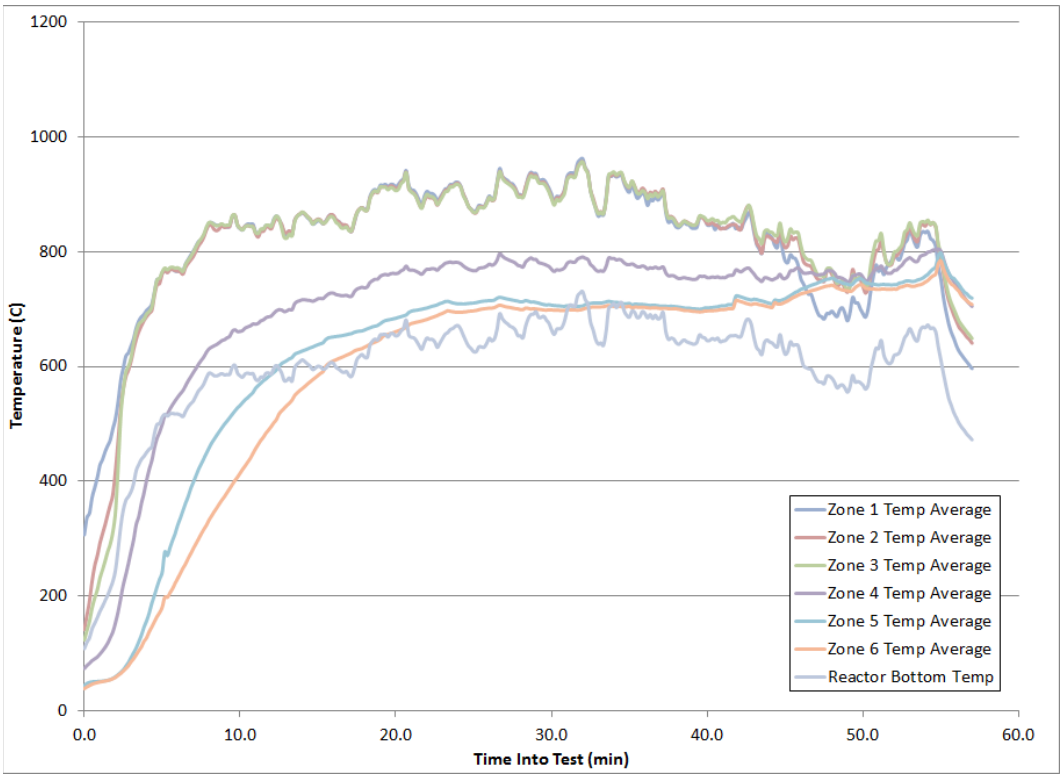
JOB#: 11201
ID#: 29323

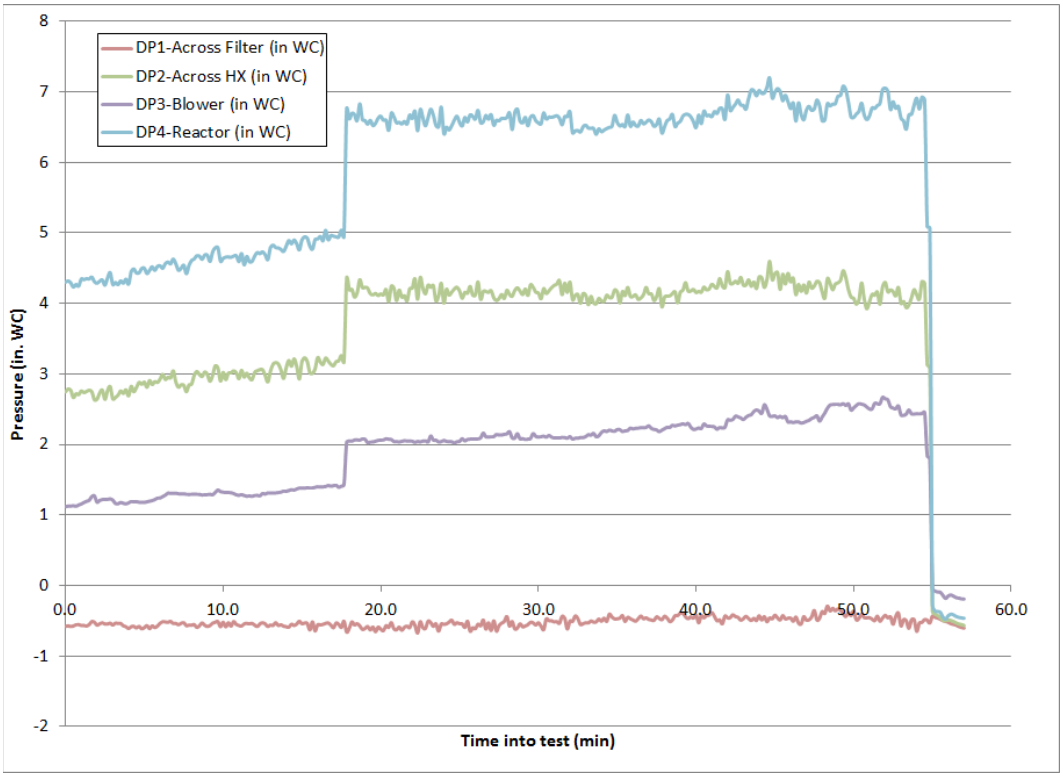


Plot 7

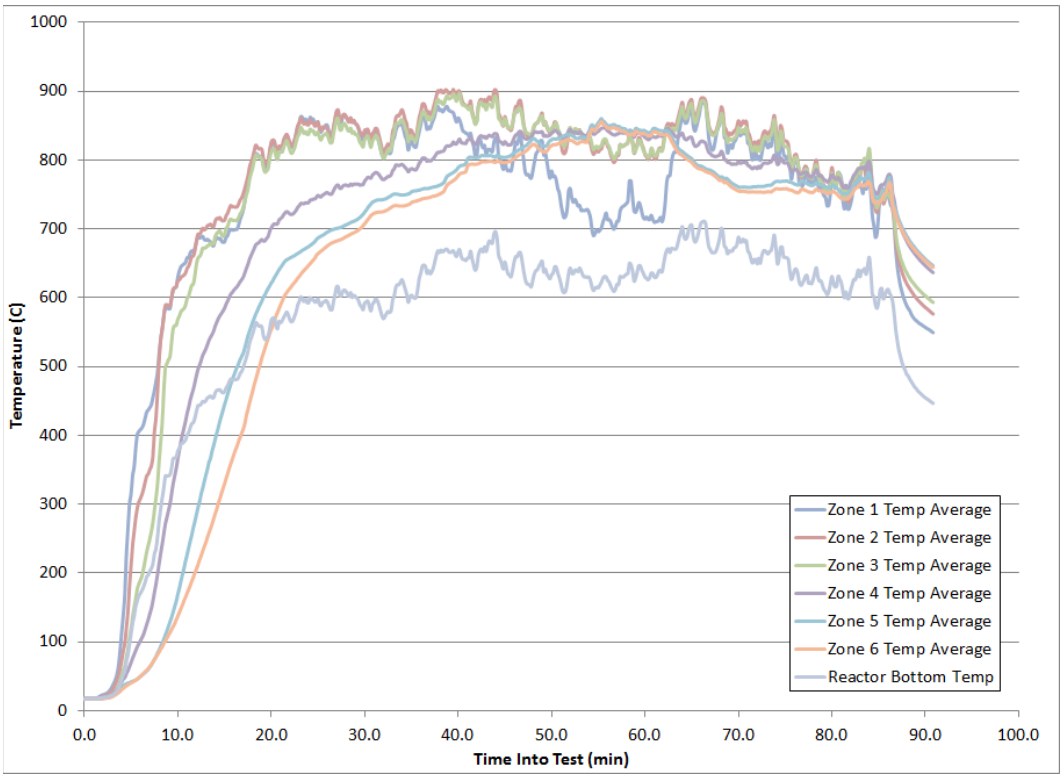
A3 Gasifier Test Plots

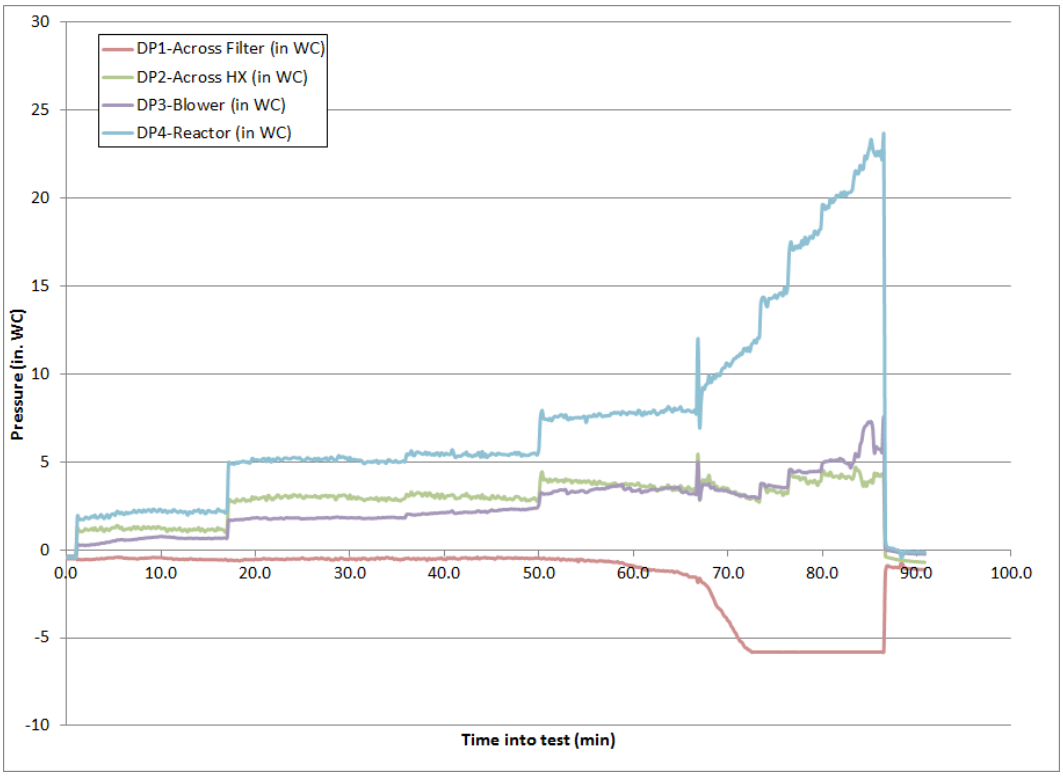
2/26/14 Test



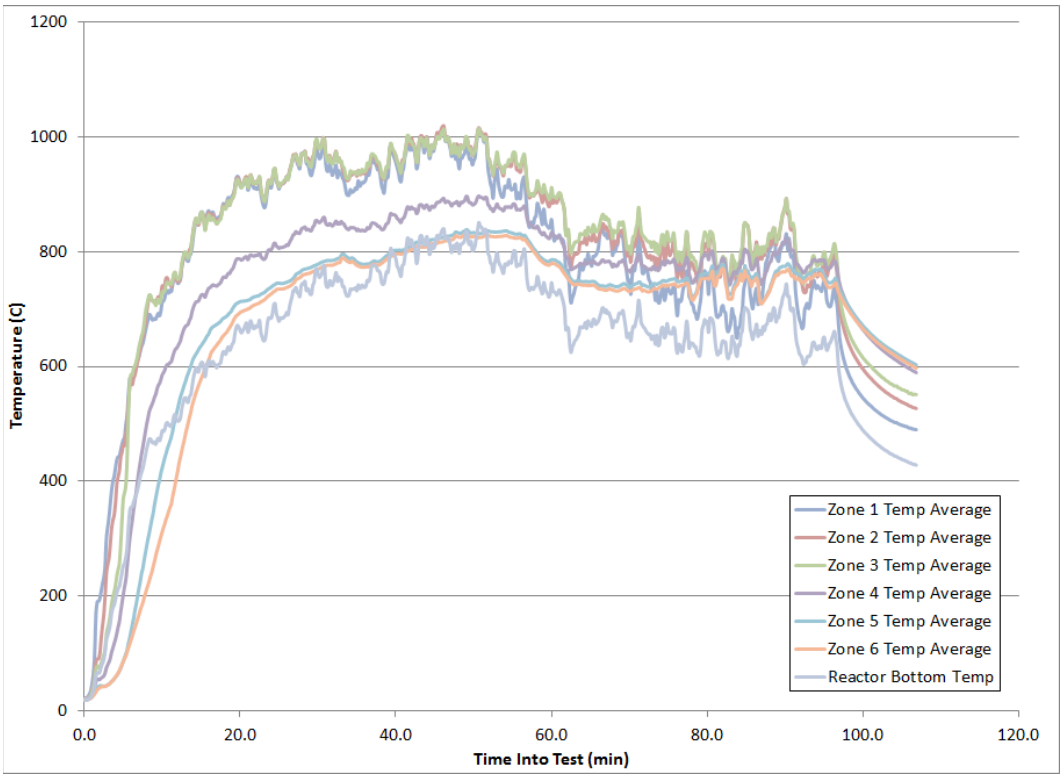


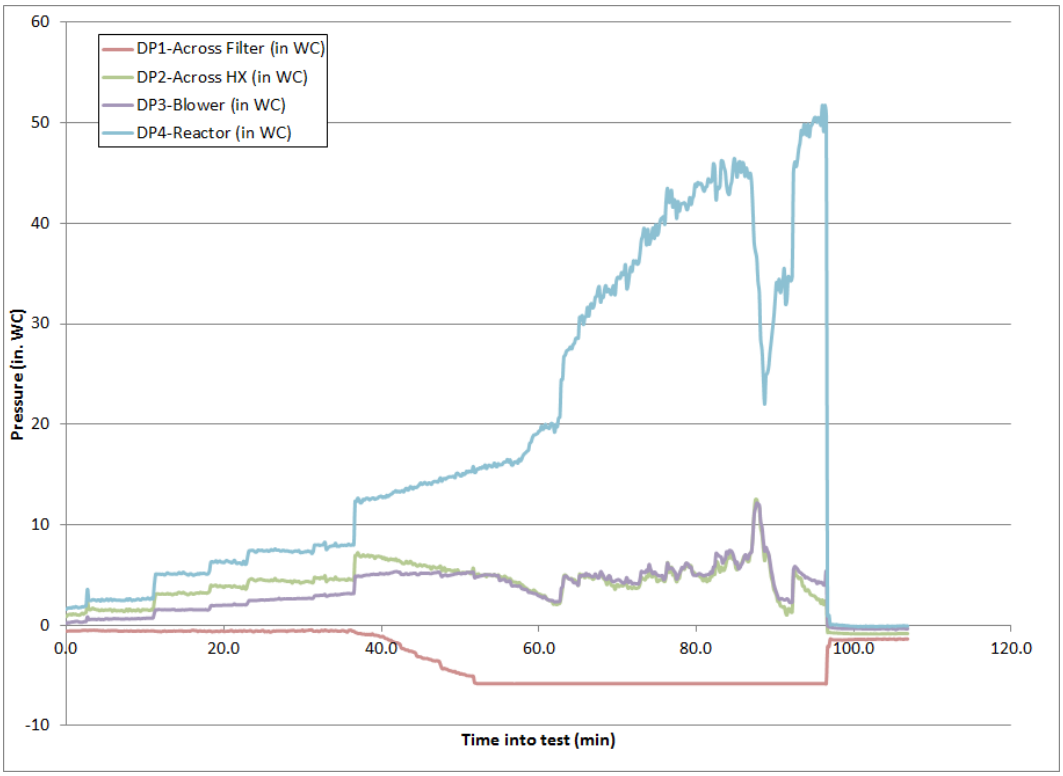
3/3/2014 Test


Temperature (C)
Time Into Test (min)
Zone 1 Temp Average
Zone 2 Temp Average
Zone 3 Temp Average
Zone 4 Temp Average
Zone 5 Temp Average
Zone 6 Temp Average
Reactor Bottom Temp

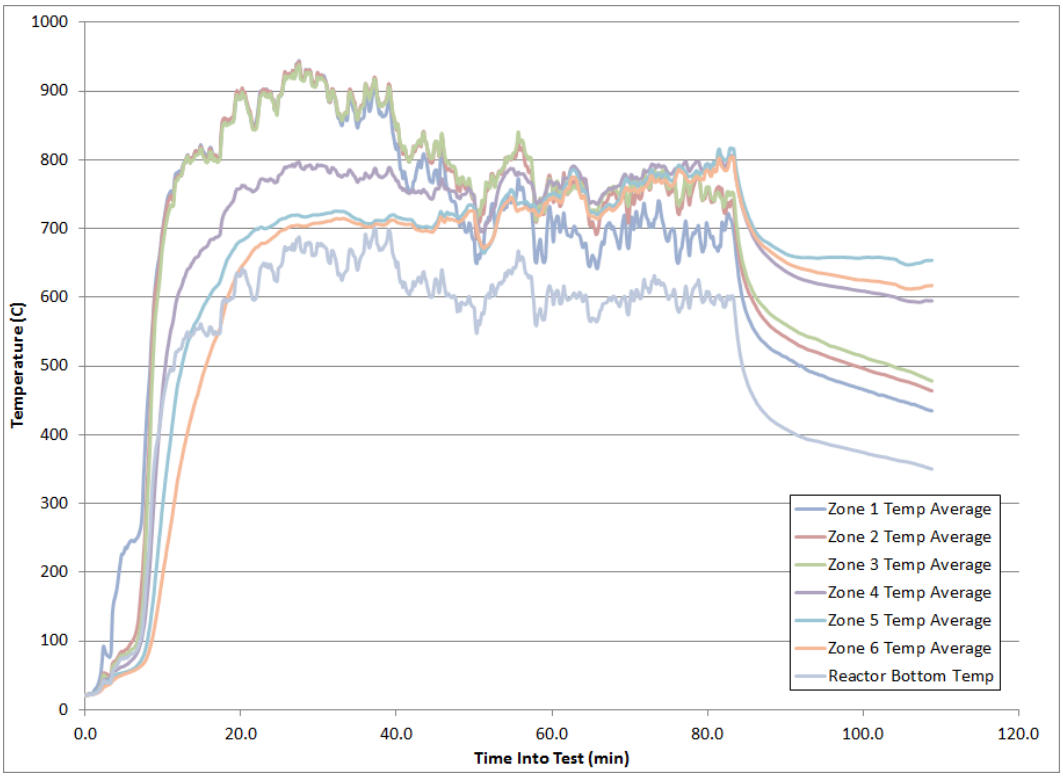

Pressure (in. WC)
Time into test (min)
DP1-Across Filter (in WC)
DP2-Across HX (in WC)
DP3-Blower (in WC)
DP4-Reactor (in WC)

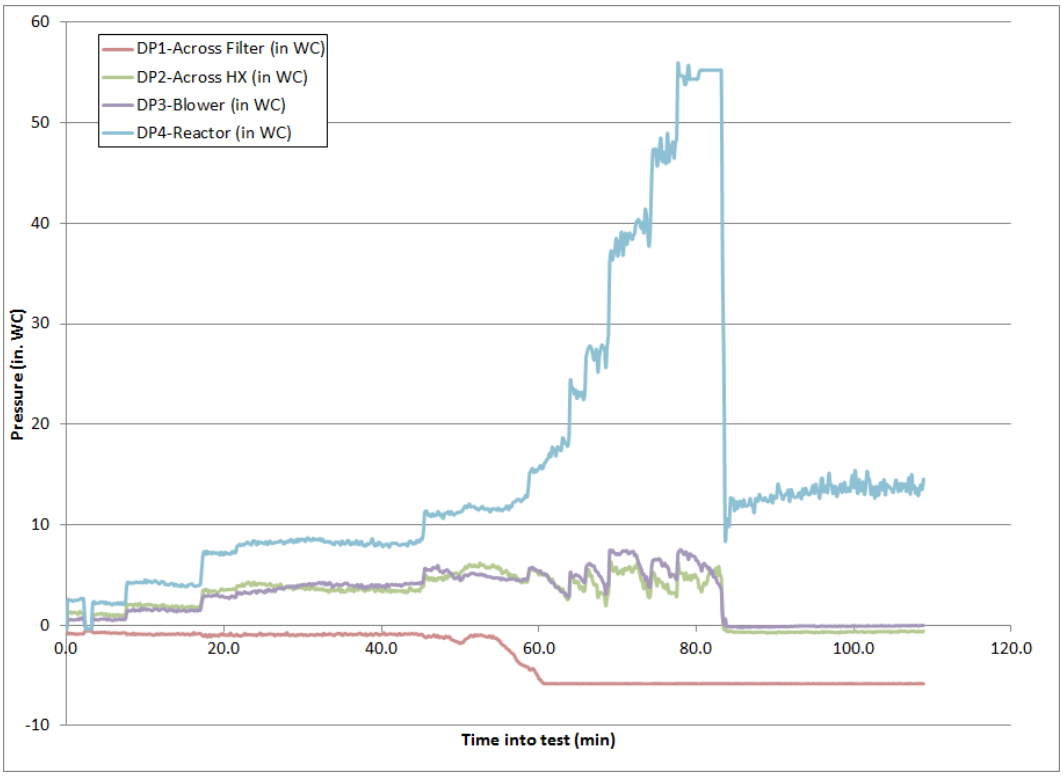
3/6/2014 Test


1200
1000
800
600
400
200
0
Temperature (C)
0.0
20.0
40.0
60.0
80.0
100.0
120.0
Time Into Test (min)
Zone 1 Temp Average
Zone 2 Temp Average
Zone 3 Temp Average
Zone 4 Temp Average
Zone 5 Temp Average
Zone 6 Temp Average
Reactor Bottom Temp

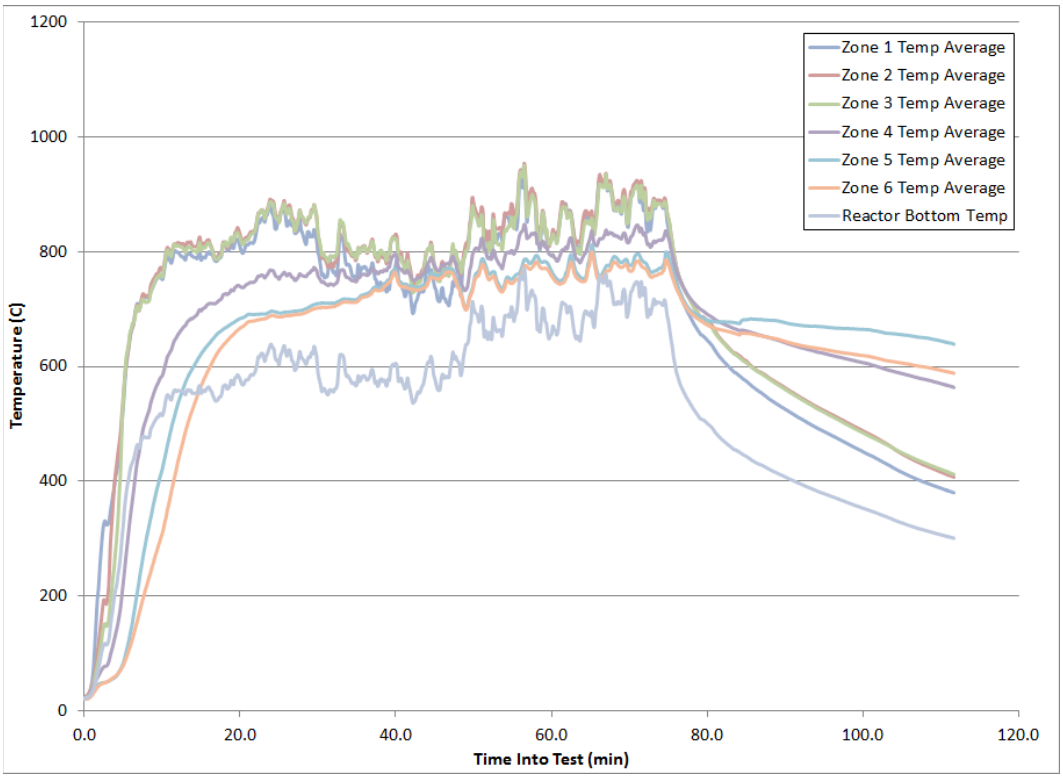

60
50
40
30
20
10
0
-10
Pressure (in. WC)
0.0
20.0
40.0
60.0
80.0
100.0
120.0
Time into test (min)
DP1-Across Filter (in WC)
DP2-Across HX (in WC)
DP3-Blower (in WC)
DP4-Reactor (in WC)

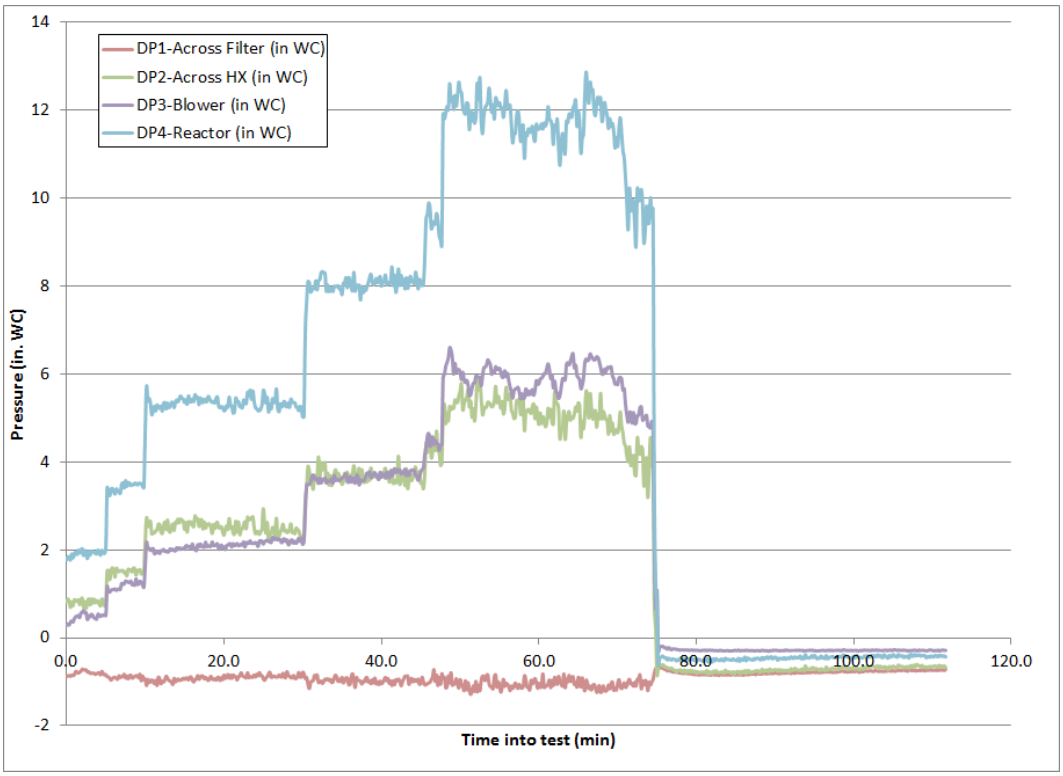
4/25/2014 Test



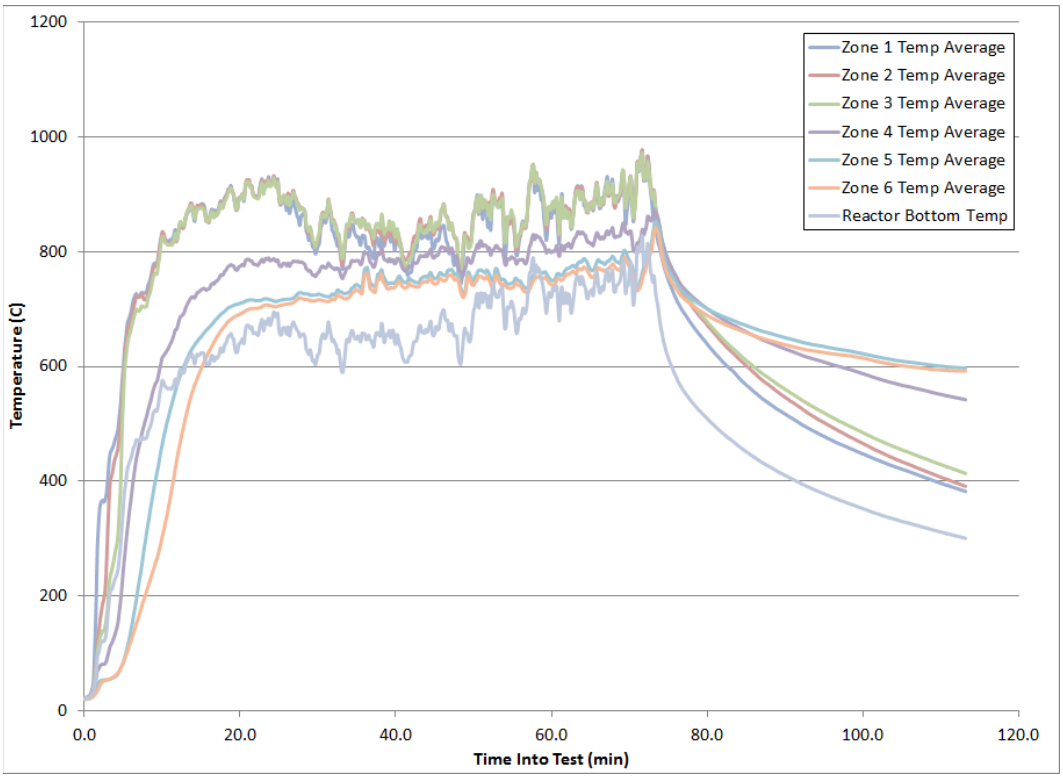


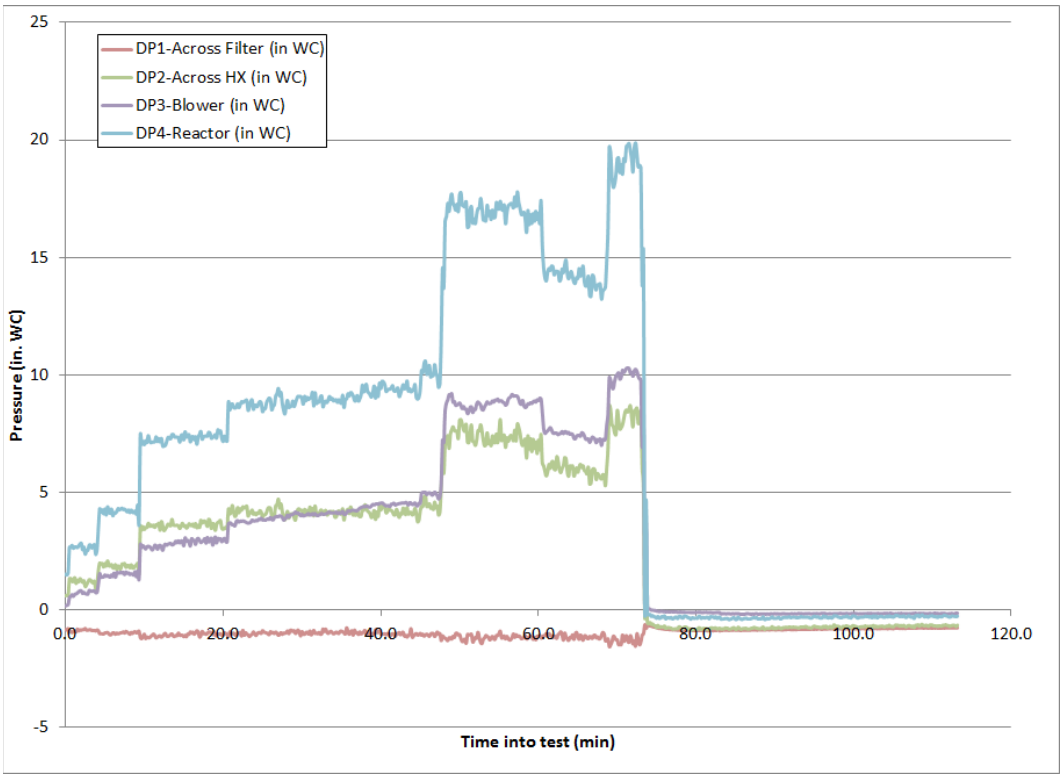
5/9/2014 Test


Zone 1 Temp Average
Zone 2 Temp Average
Zone 3 Temp Average
Zone 4 Temp Average
Zone 5 Temp Average
Zone 6 Temp Average
Reactor Bottom Temp
Temperature (C)
Time Into Test (min)
0
200
400
600
800
1000
1200
0.0
20.0
40.0
60.0
80.0
100.0
120.0

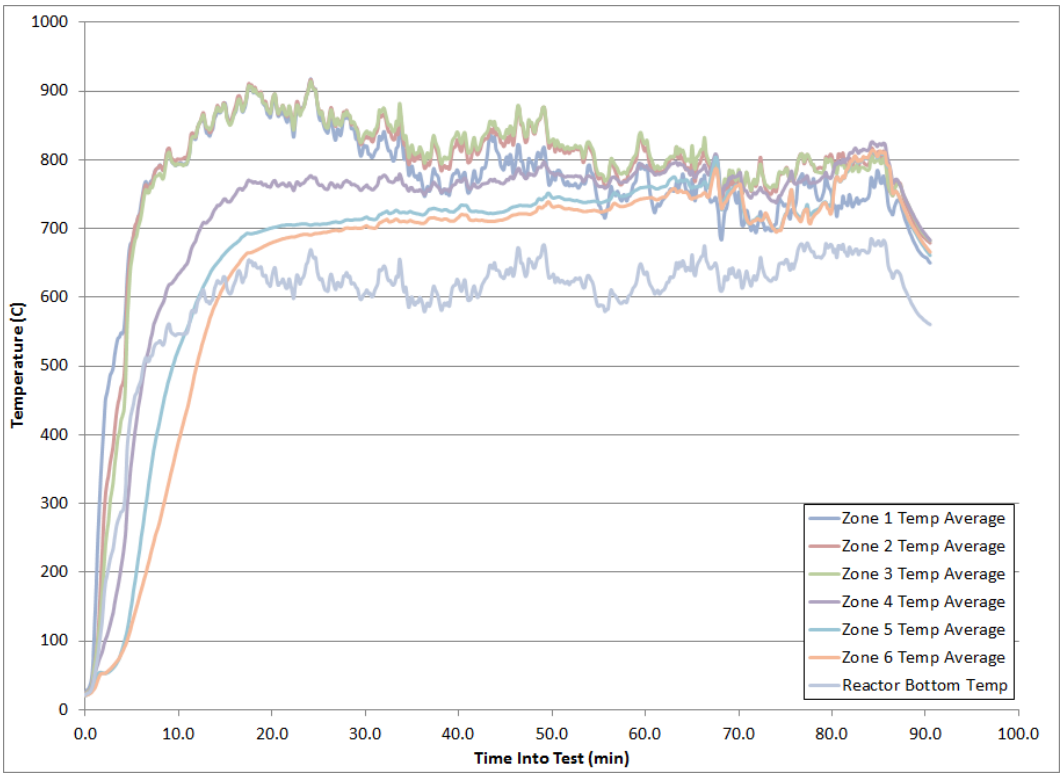

DP1-Across Filter (in WC)
DP2-Across HX (in WC)
DP3-Blower (in WC)
DP4-Reactor (in WC)
Pressure (in. WC)
Time into test (min)
-2
0
2
4
6
8
10
12
14
0.0
20.0
40.0
60.0
80.0
100.0
120.0

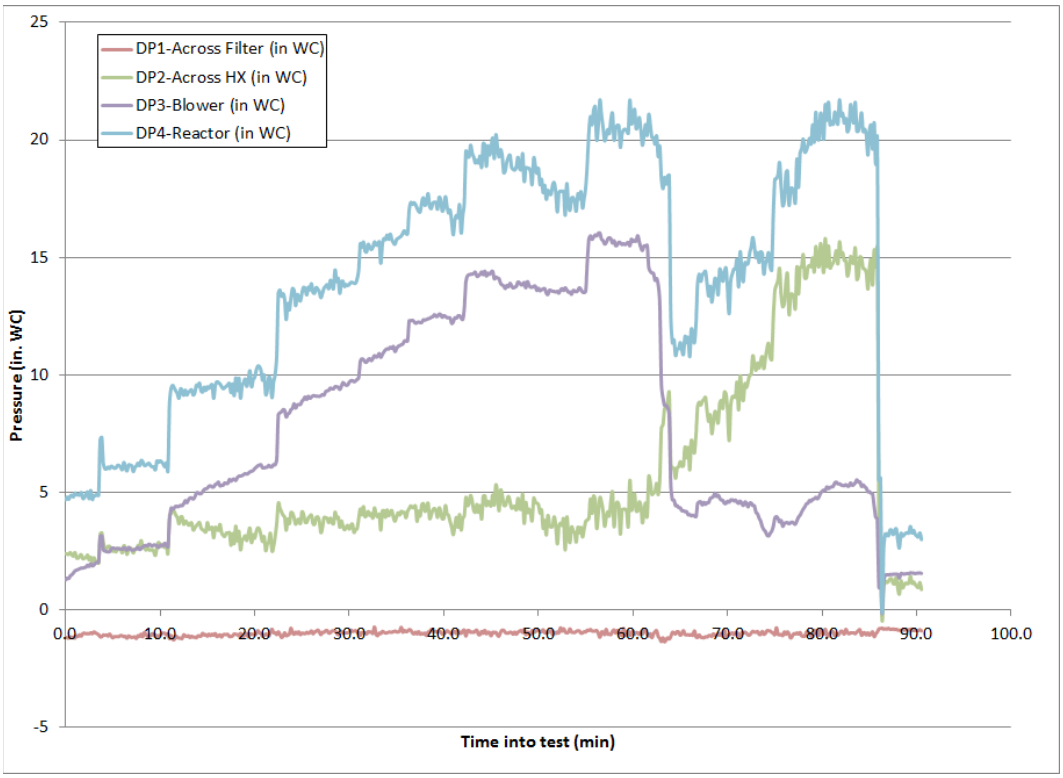
5/13/2014 Test



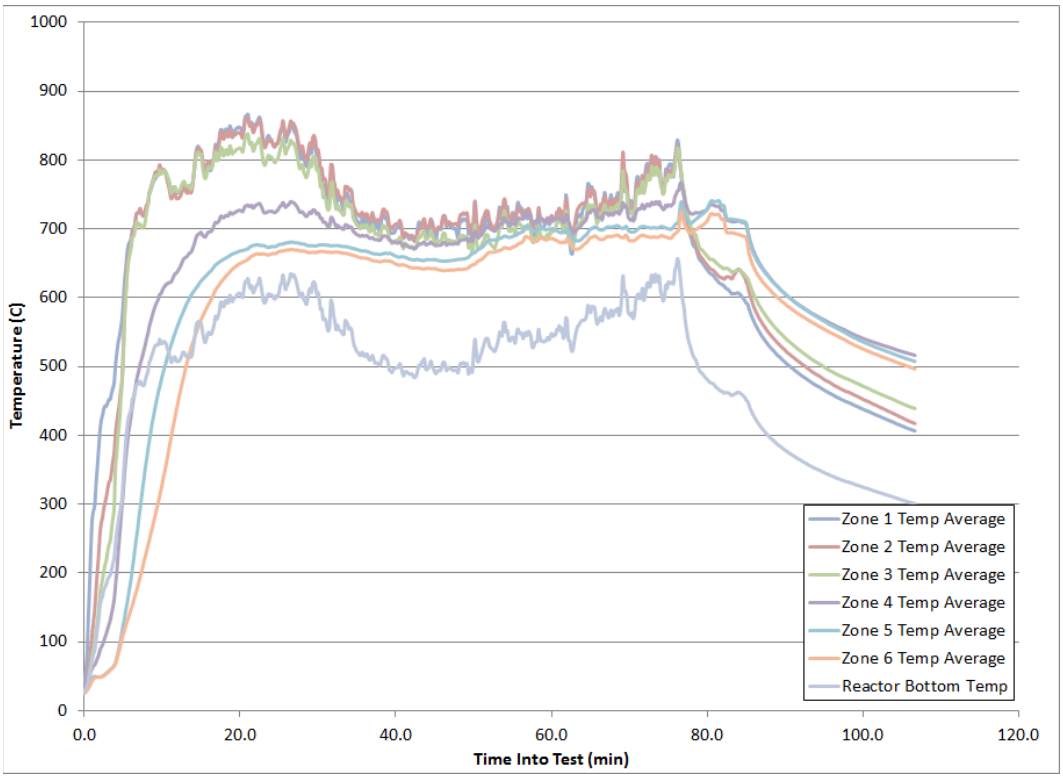


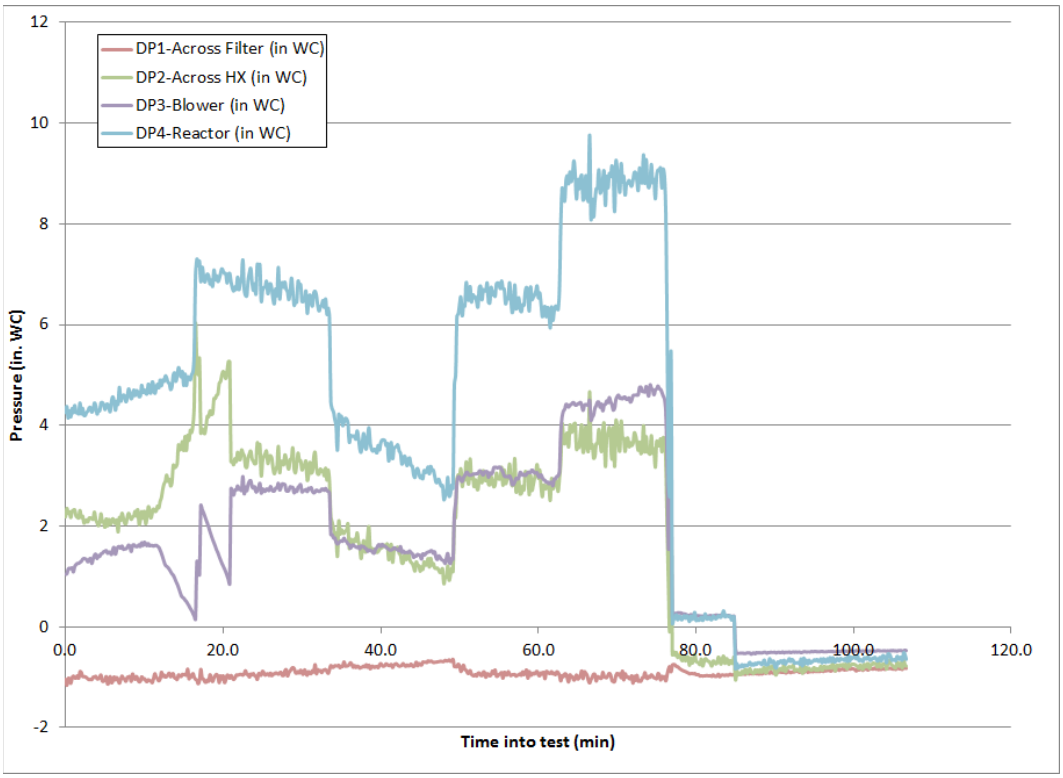
5/16/2014 Test



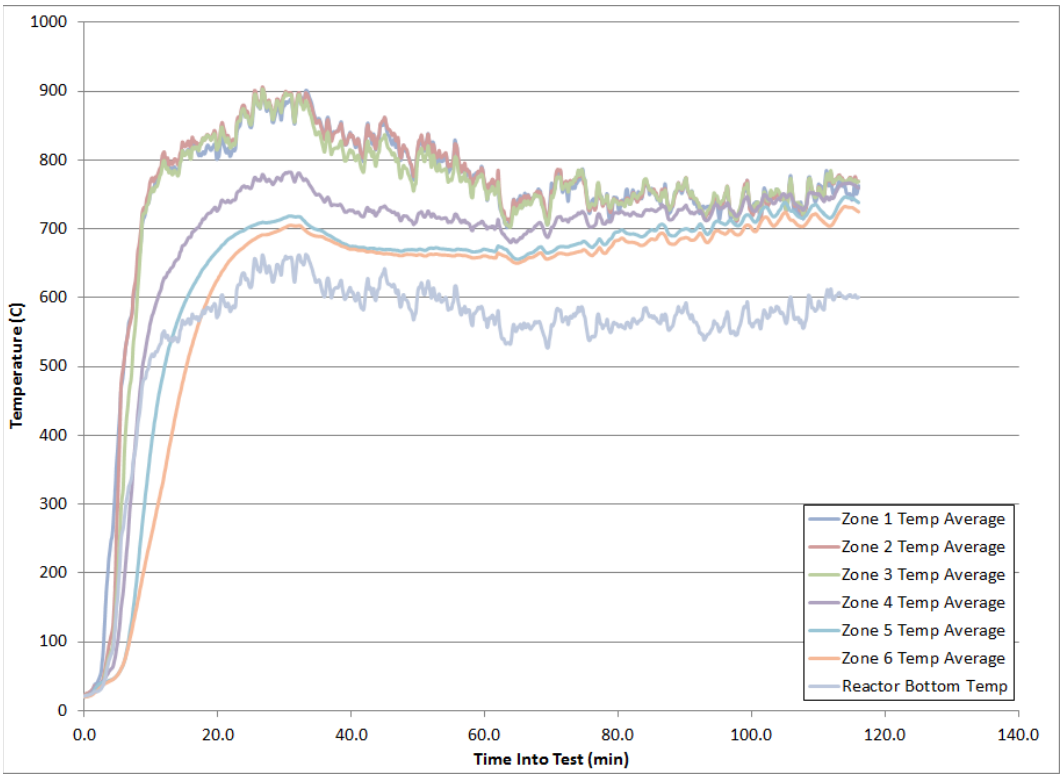


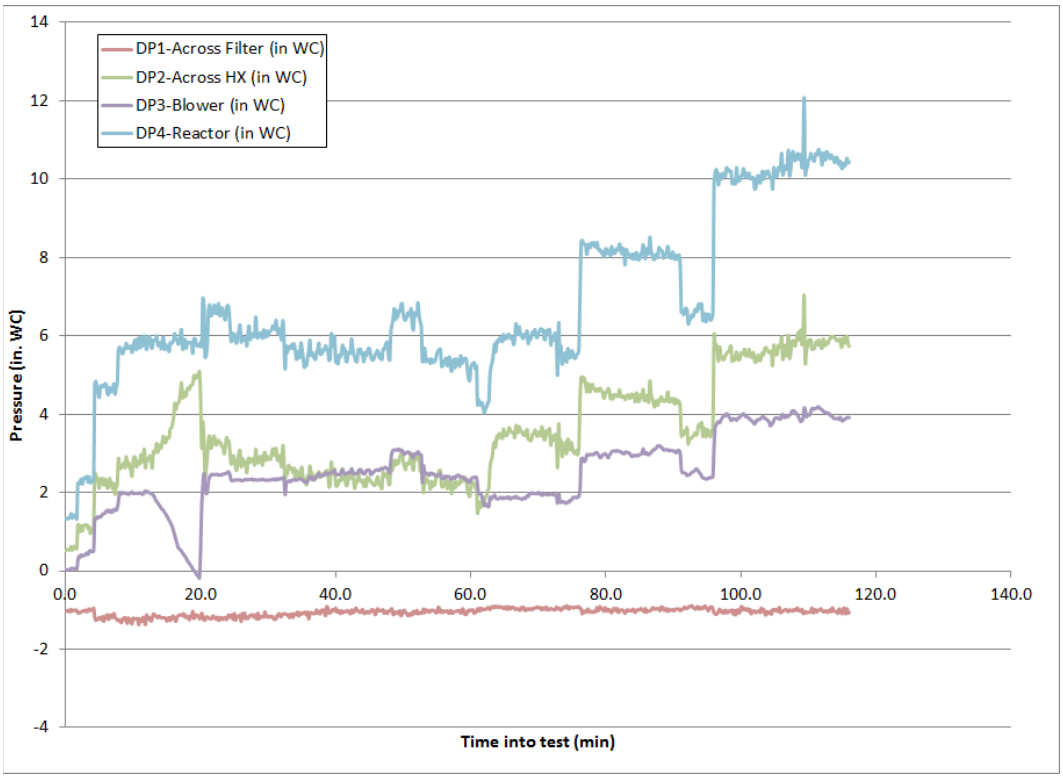
5/22/2014 Test



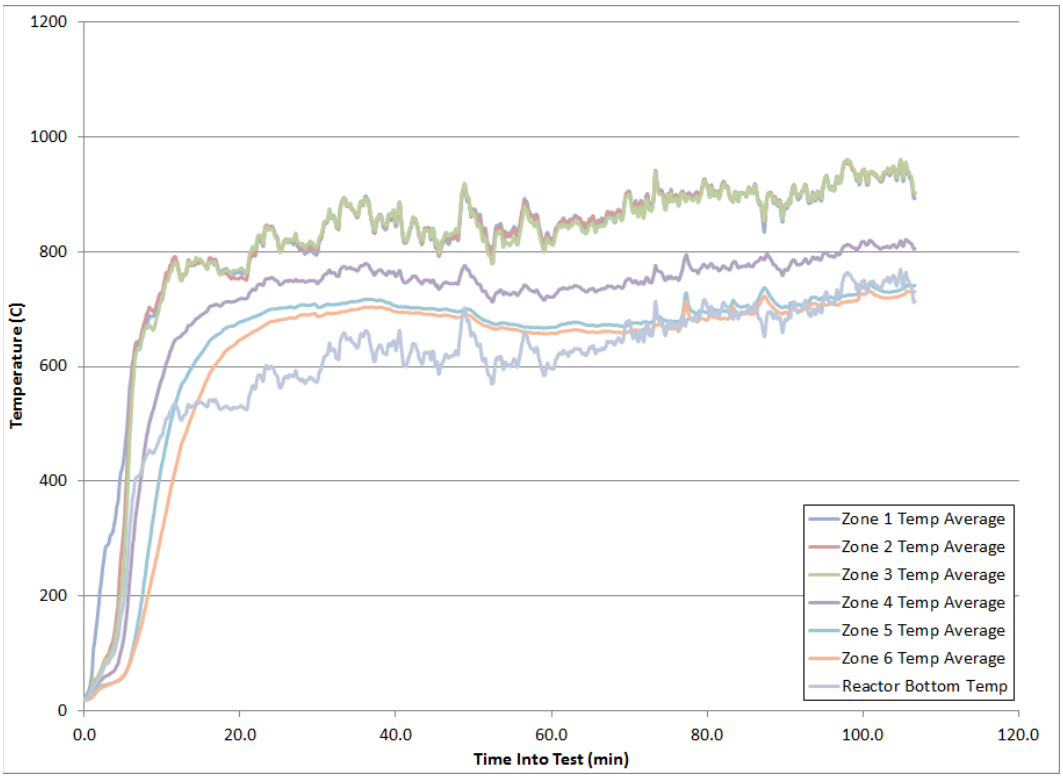


6/5/2014 Test


Temperature (C)
Time Into Test (min)
Zone 1 Temp Average
Zone 2 Temp Average
Zone 3 Temp Average
Zone 4 Temp Average
Zone 5 Temp Average
Zone 6 Temp Average
Reactor Bottom Temp

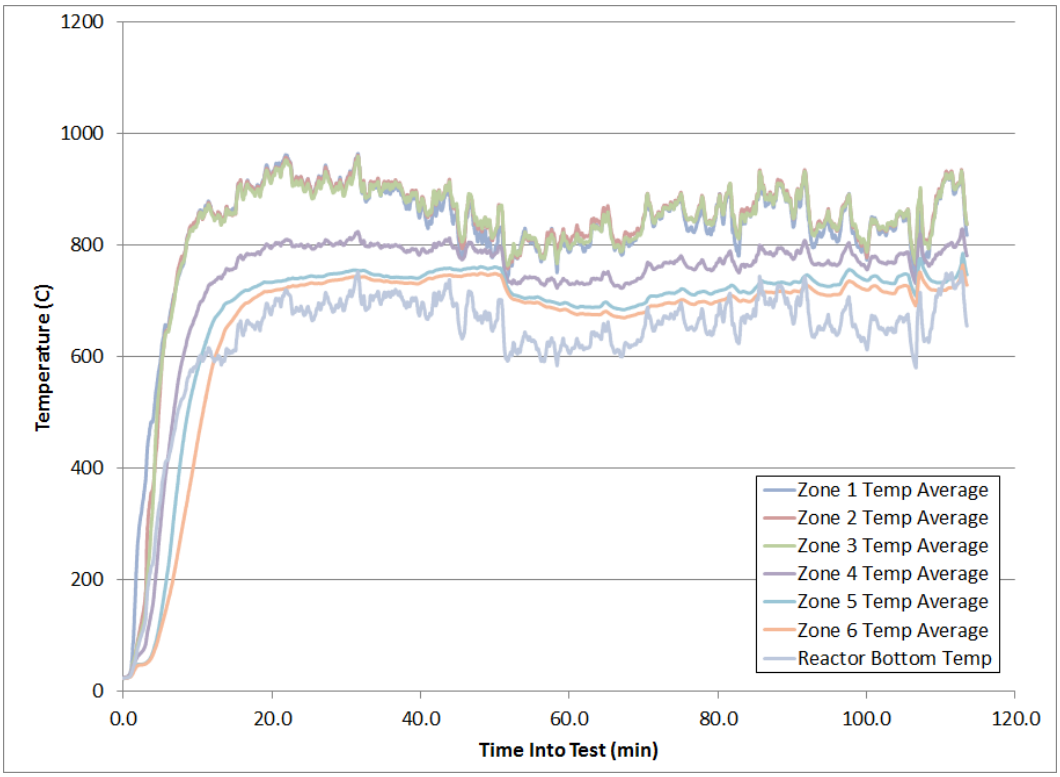

Pressure (in. WC)
Time into test (min)
DP1-Across Filter (in WC)
DP2-Across HX (in WC)
DP3-Blower (in WC)
DP4-Reactor (in WC)

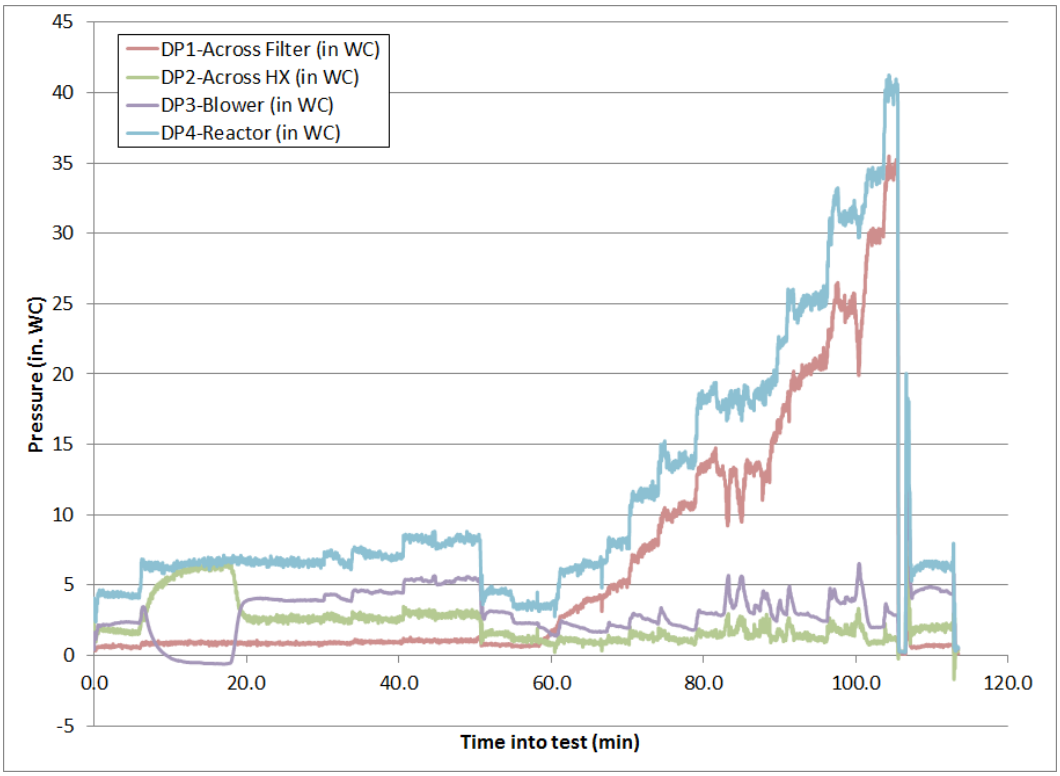
6/12/2014


1200
1000
800
600
400
200
0
Temperature (C)
0.0
20.0
40.0
60.0
80.0
100.0
120.0
Time Into Test (min)
Zone 1 Temp Average
Zone 2 Temp Average
Zone 3 Temp Average
Zone 4 Temp Average
Zone 5 Temp Average
Zone 6 Temp Average
Reactor Bottom Temp

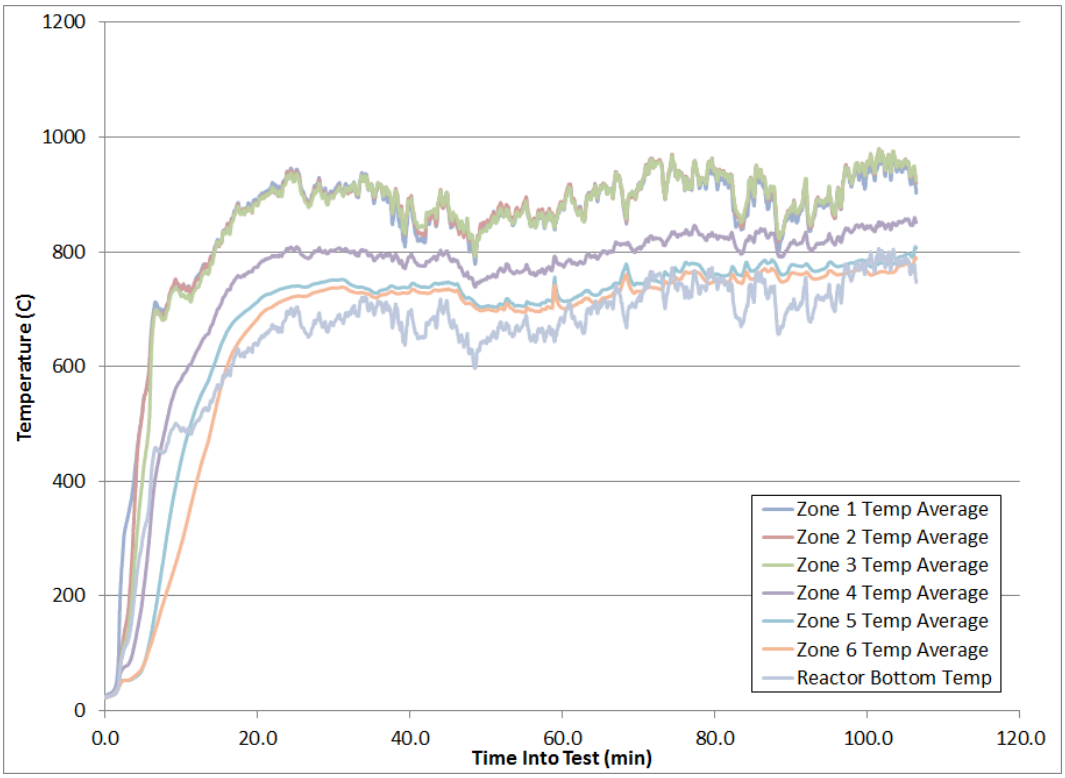
10
8
6
4
2
0
-2
Pressure (in. WC)
0.0
20.0
40.0
60.0
80.0
100.0
120.0
Time into test (min)
DP1-Across Filter (in WC)
DP2-Across HX (in WC)
DP3-Blower (in WC)
DP4-Reactor (in WC)

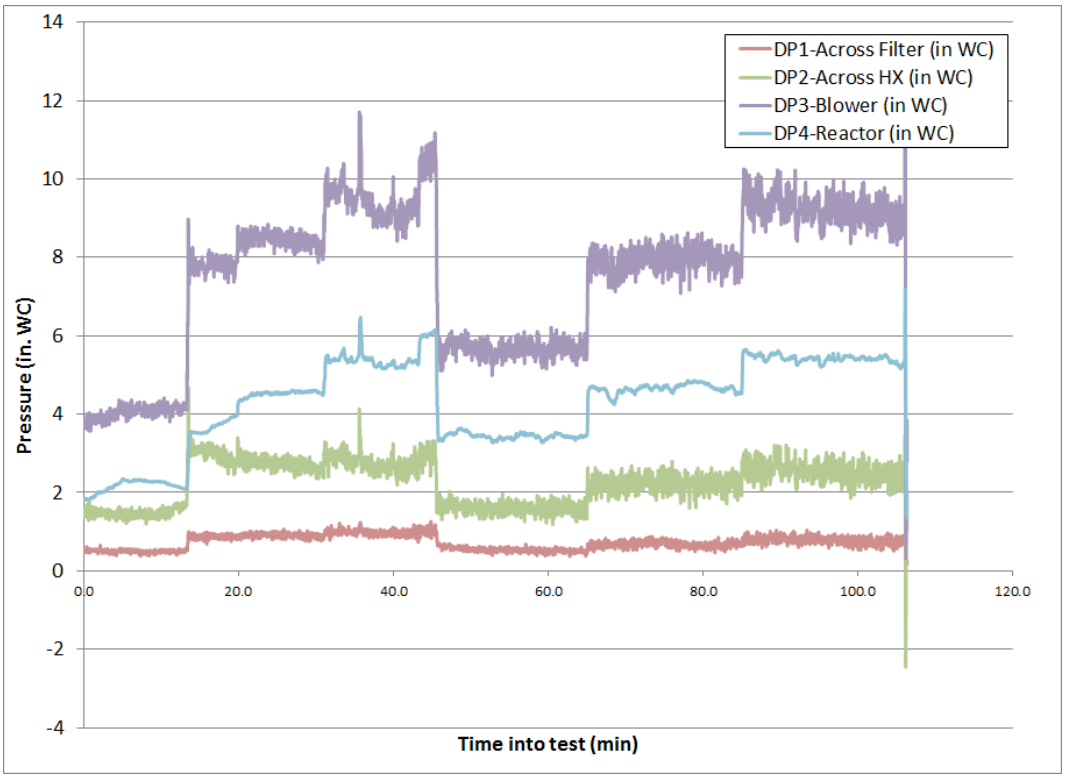
8/28/2014 Test



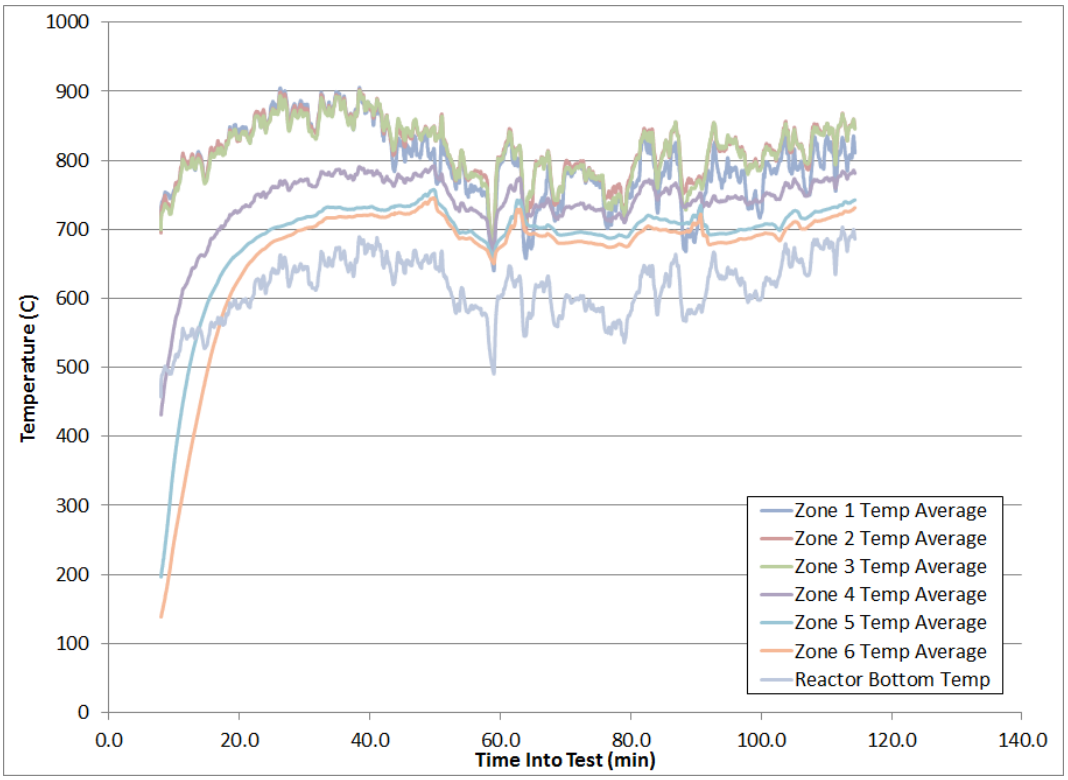


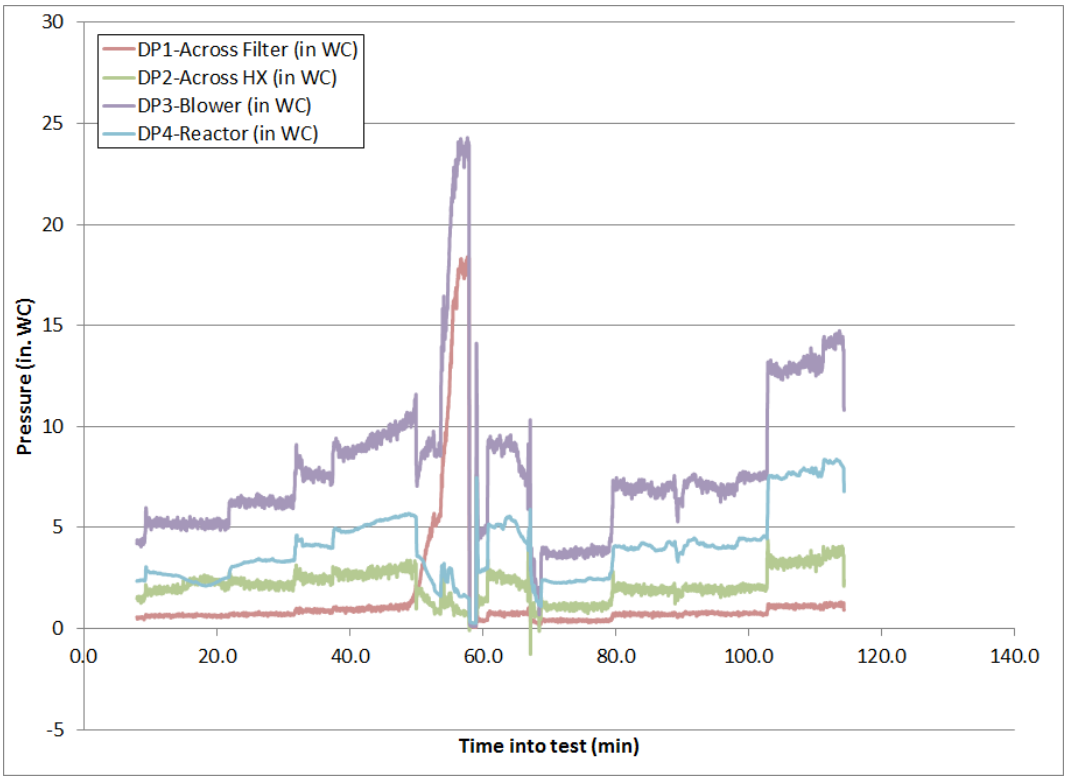
9/5/2014 Test


1200
1000
800
600
400
200
0
Temperature (C)
0.0
20.0
40.0
60.0
80.0
100.0
120.0
Time Into Test (min)
Zone 1 Temp Average
Zone 2 Temp Average
Zone 3 Temp Average
Zone 4 Temp Average
Zone 5 Temp Average
Zone 6 Temp Average
Reactor Bottom Temp

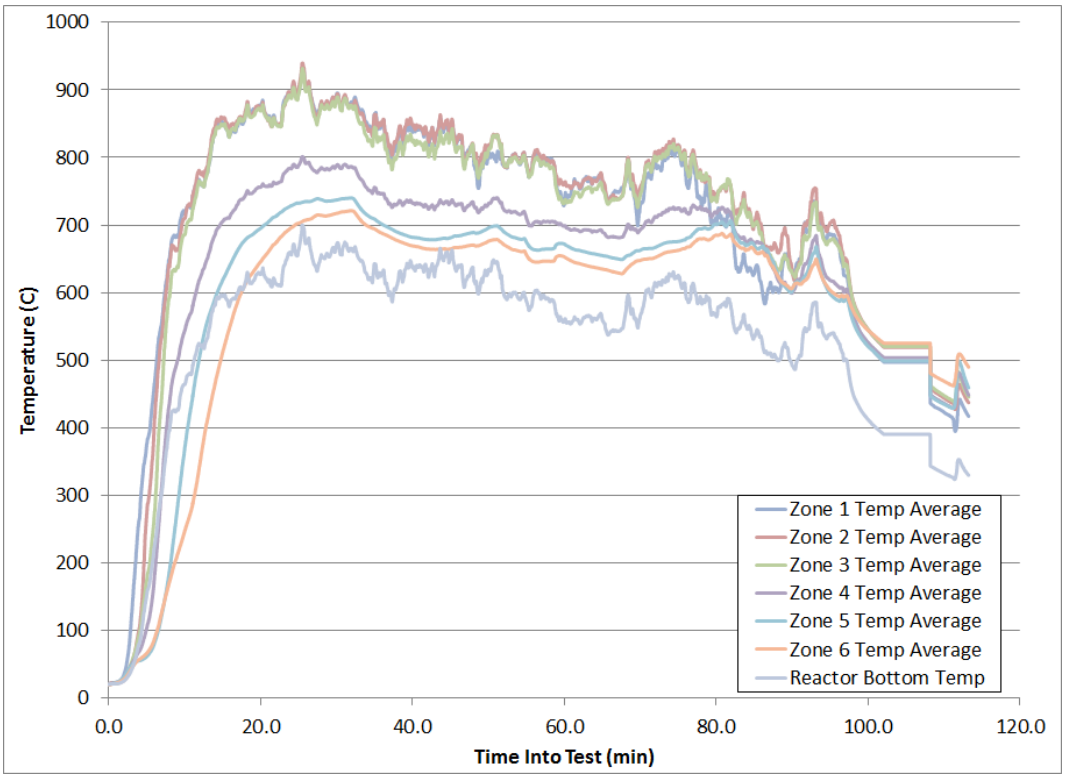

14
12
10
8
6
4
2
0
-2
-4
Pressure (in. WC)
0.0
20.0
40.0
60.0
80.0
100.0
120.0
Time into test (min)
DP1-Across Filter (in WC)
DP2-Across HX (in WC)
DP3-Blower (in WC)
DP4-Reactor (in WC)

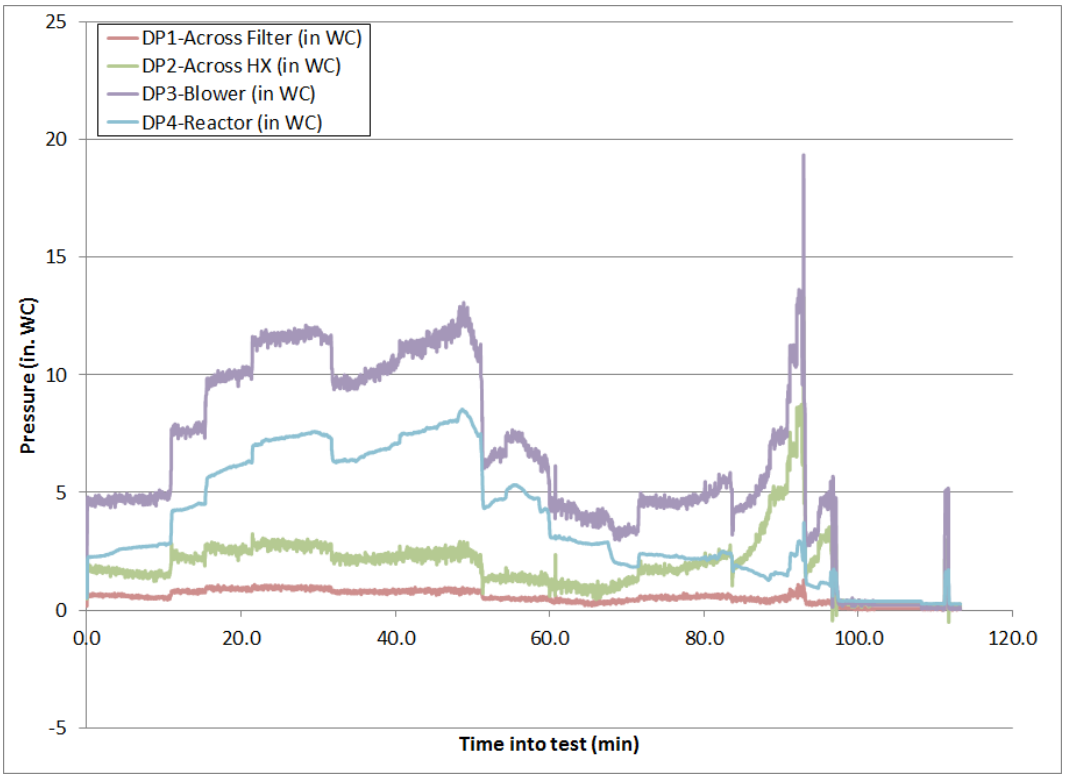
9/10/2014 Test



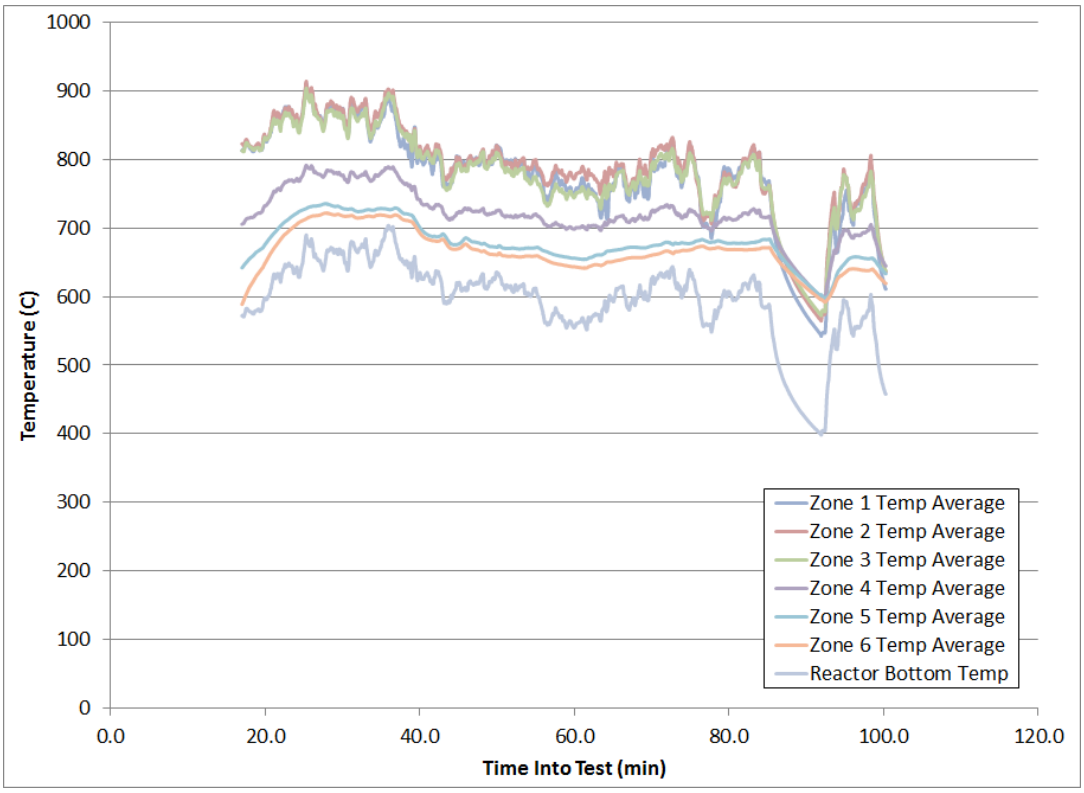


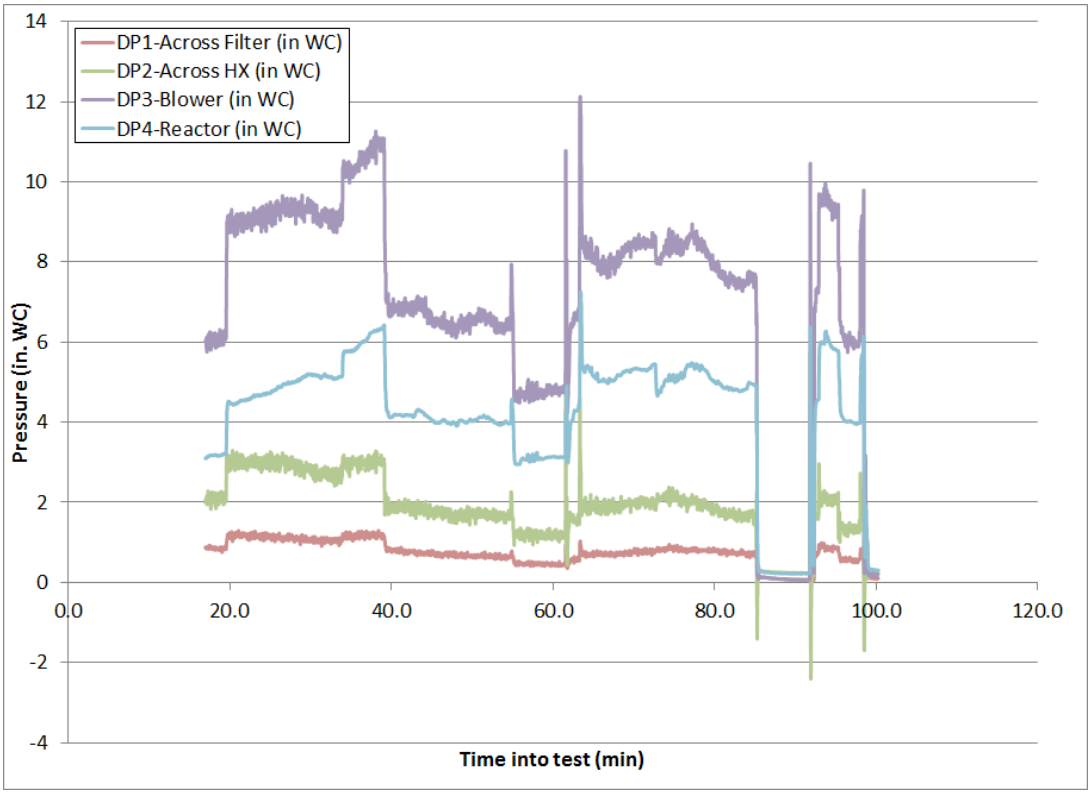
9/17/2014 Test



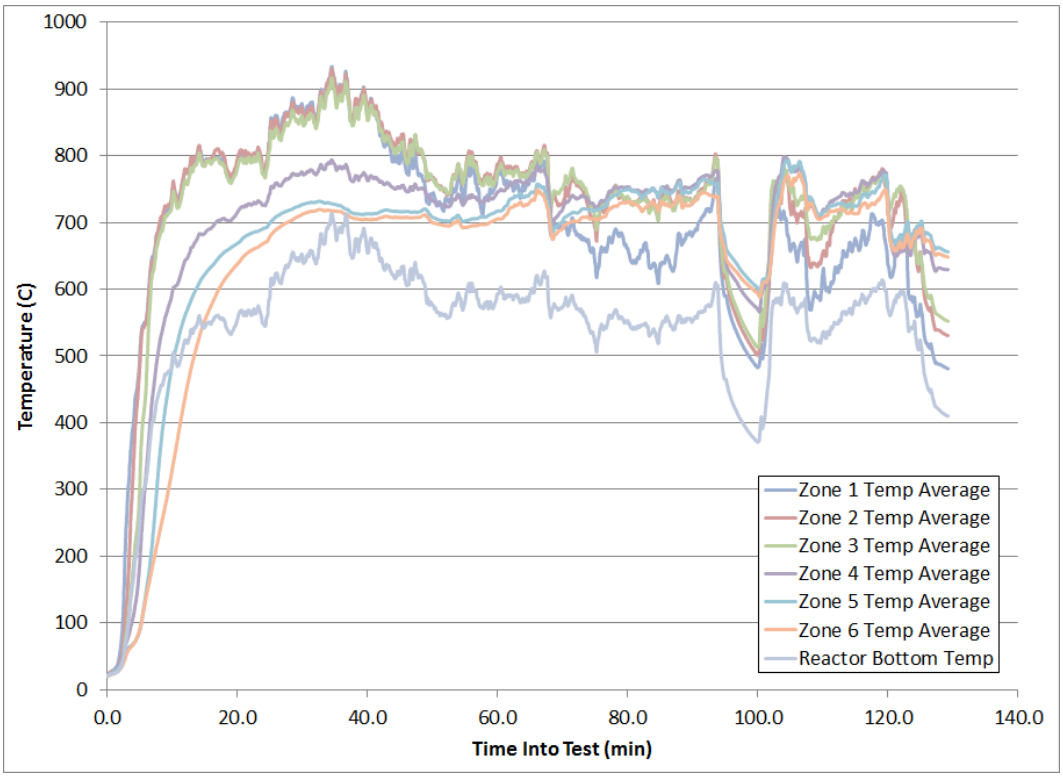


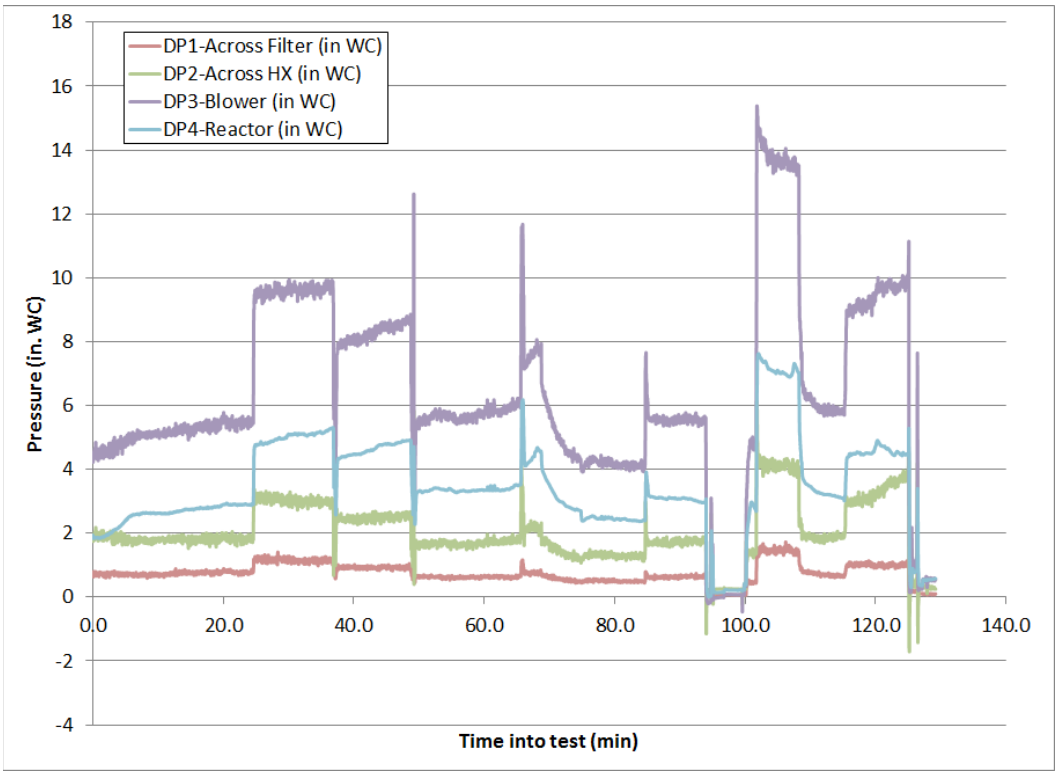
9/23/2014 Test



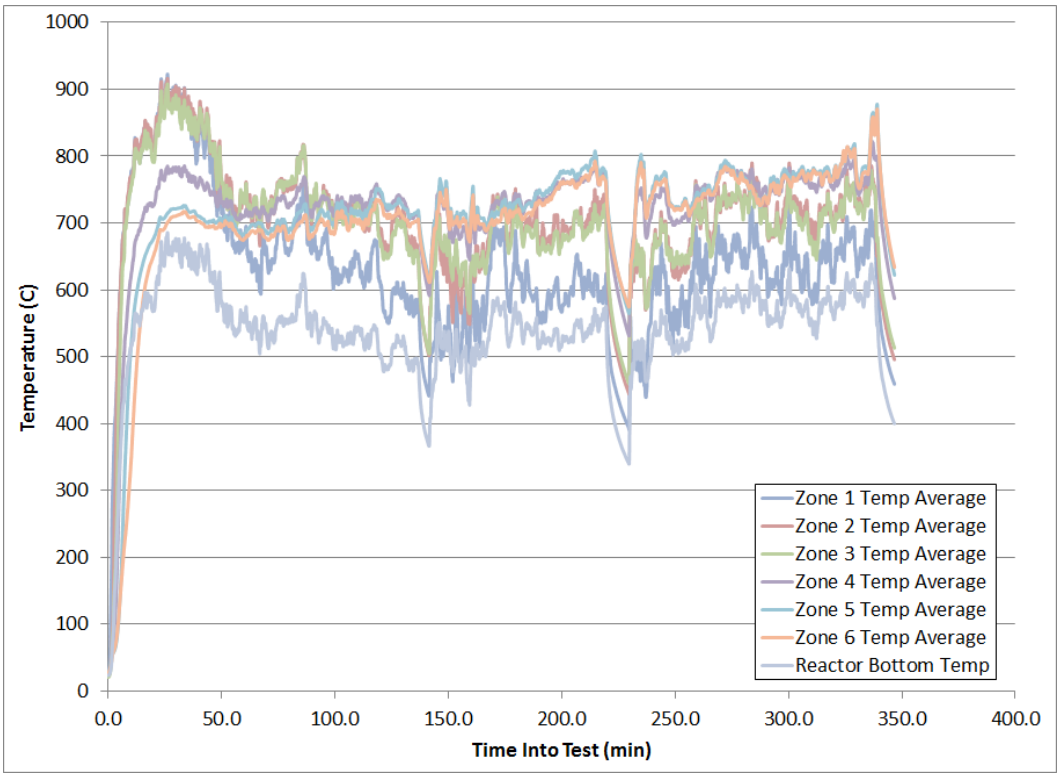


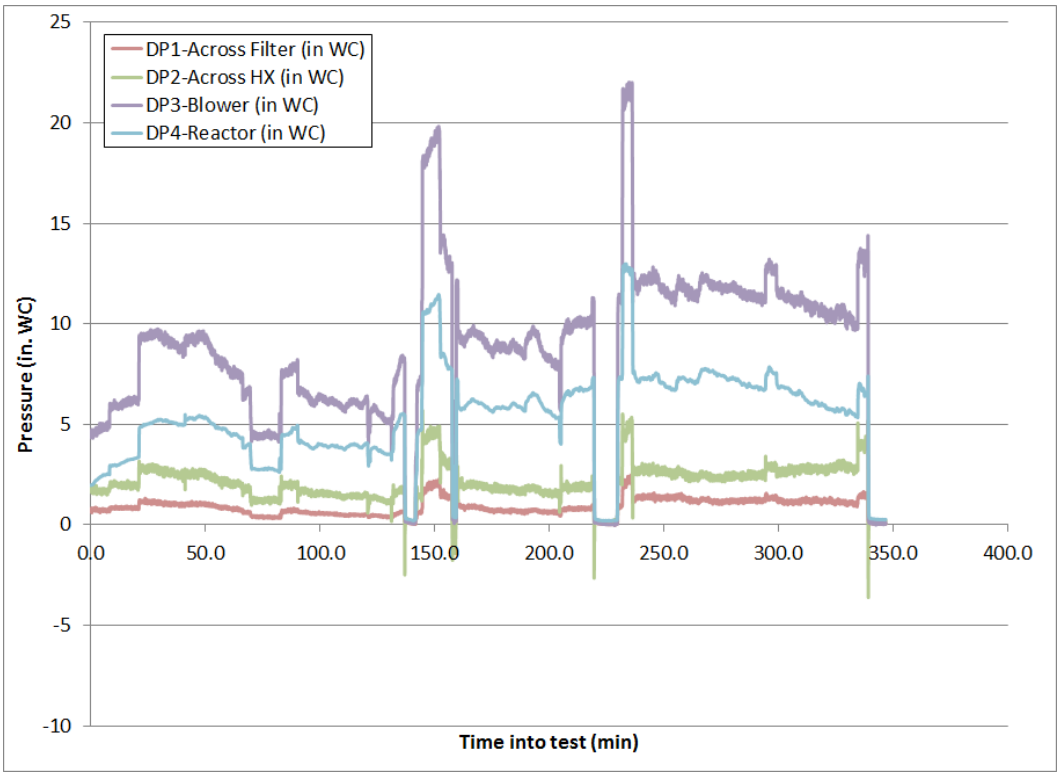
9/26/2014 Test



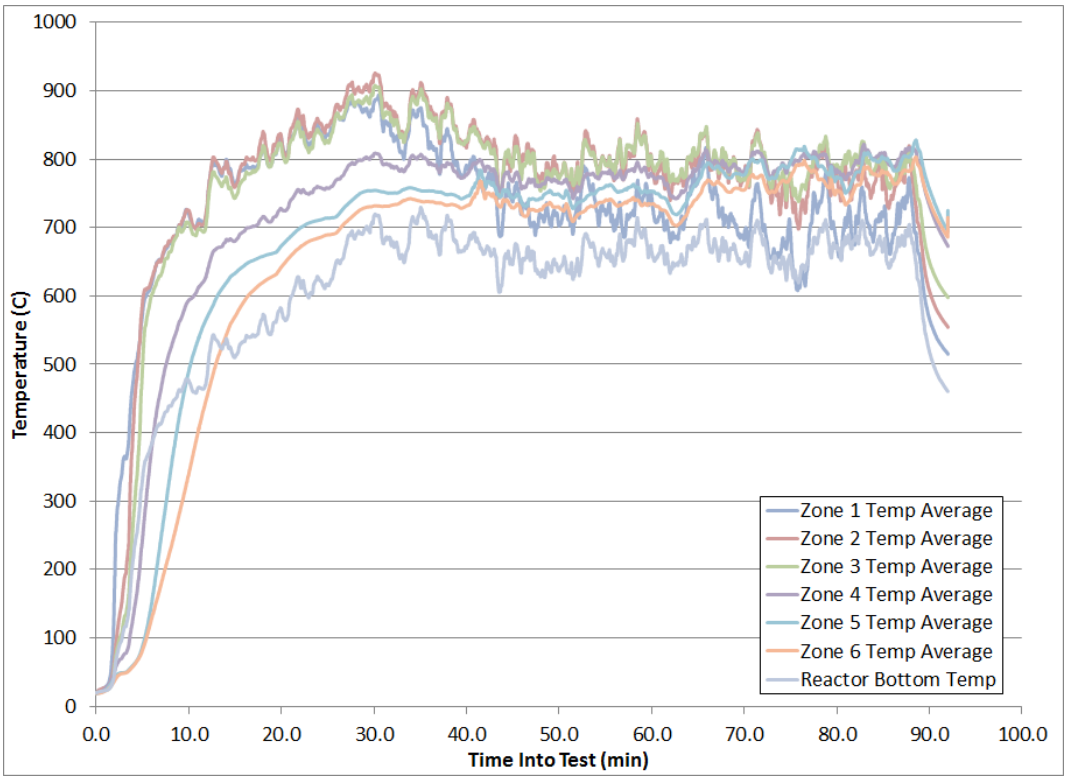


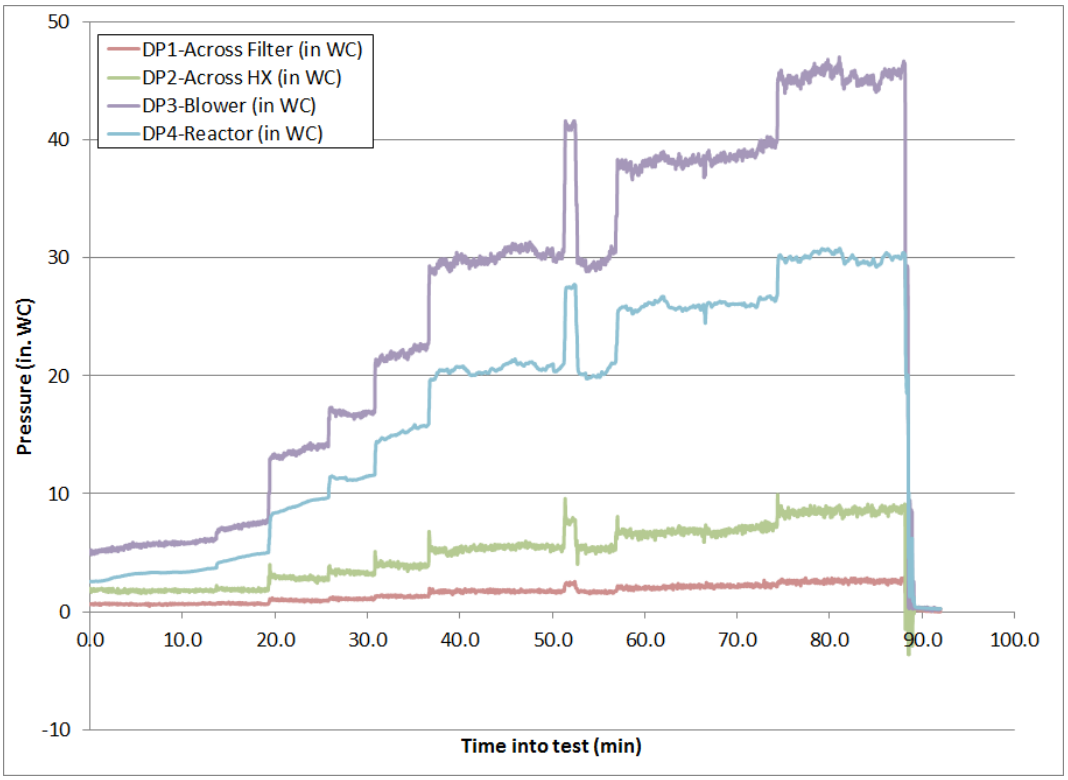
10/1/2014 Test



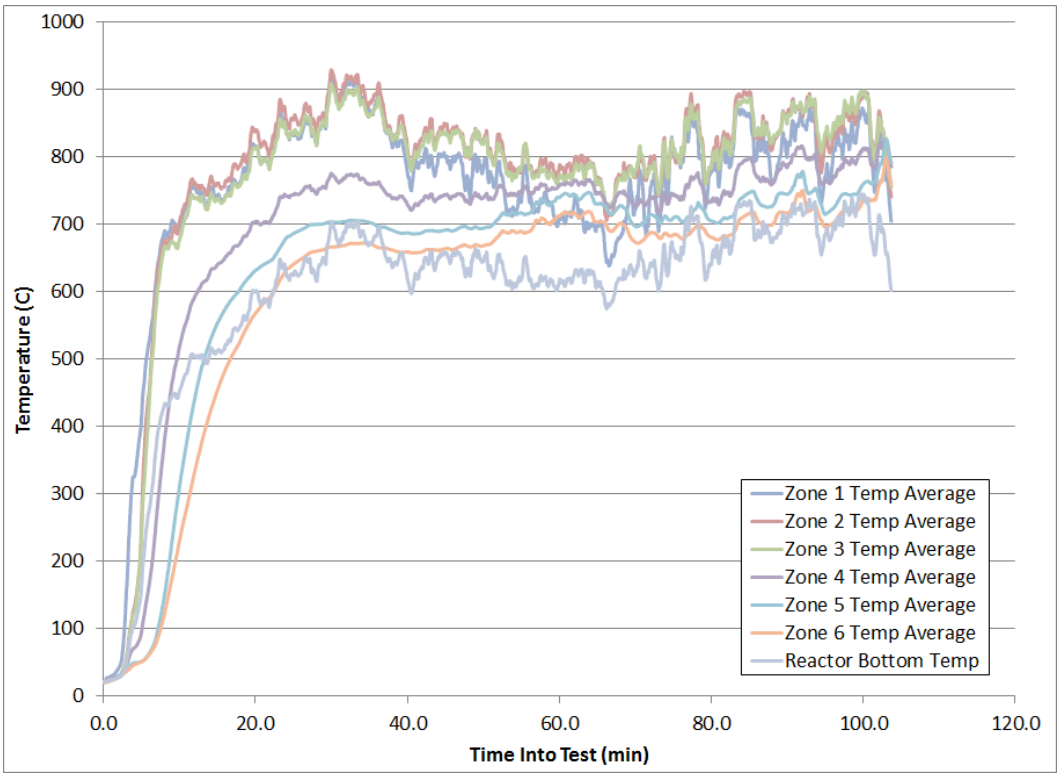


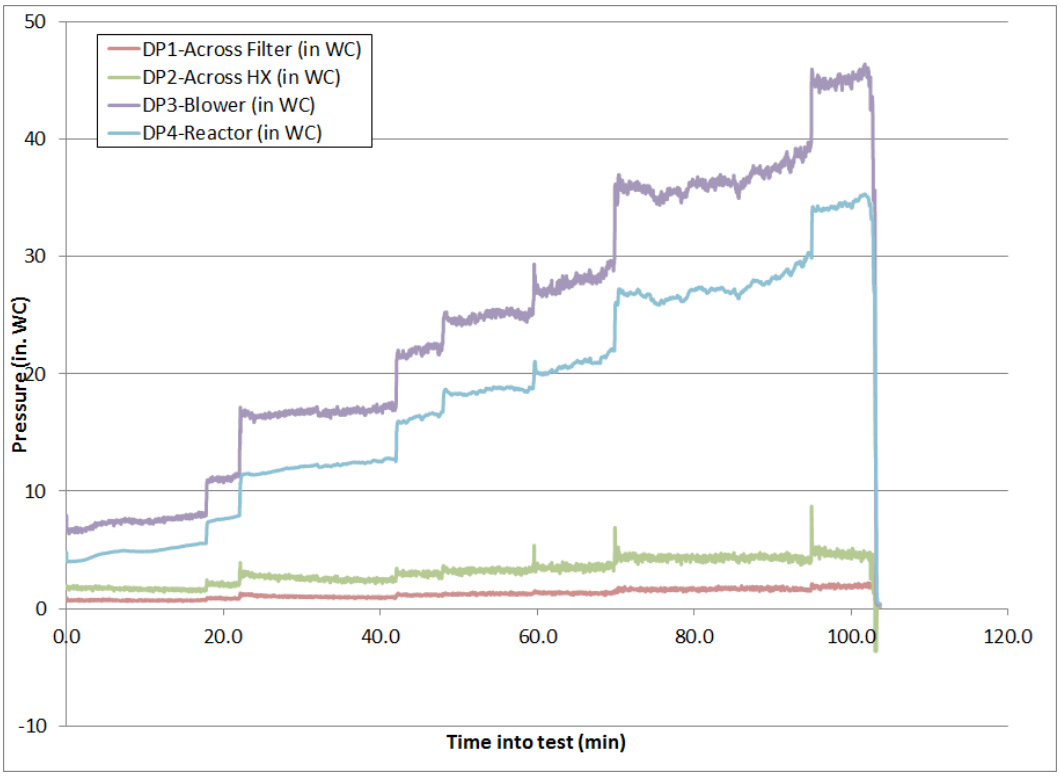
10/27/2014 Test



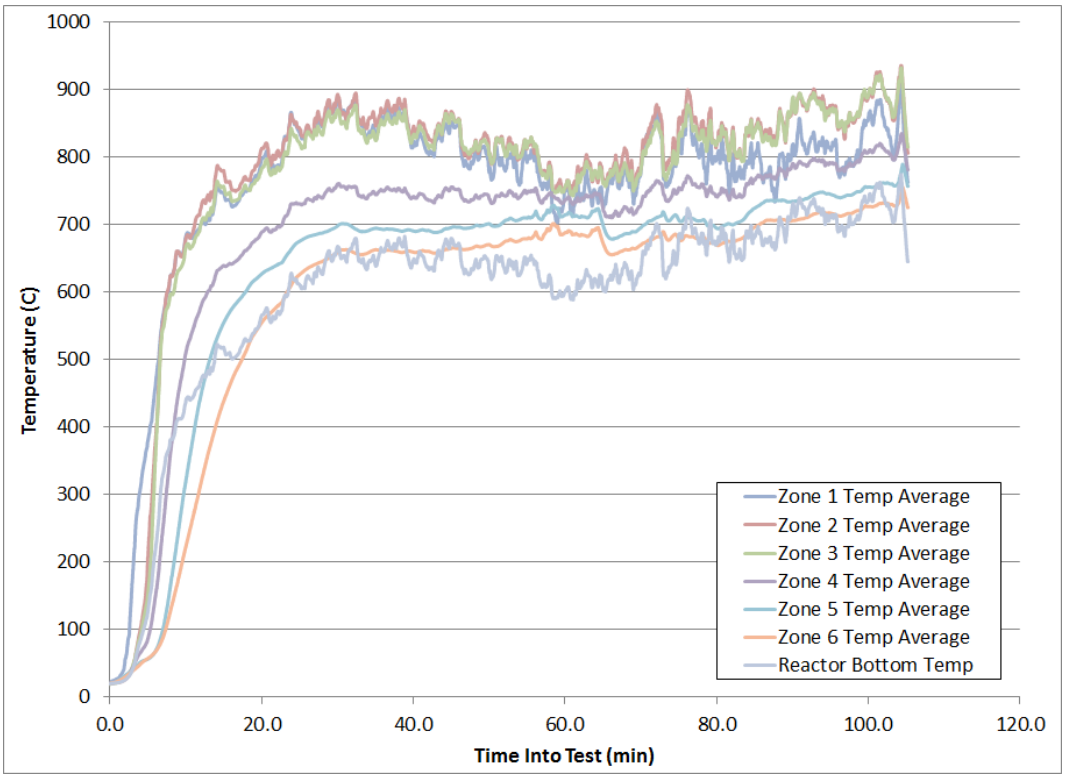


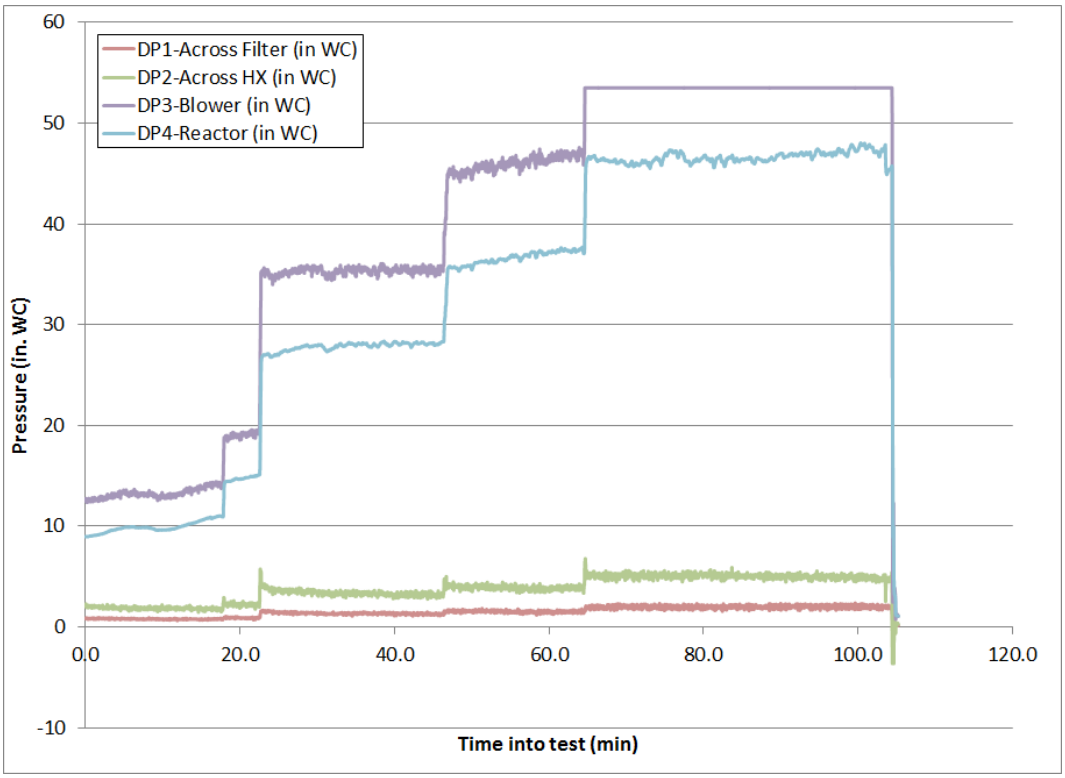
10/29/2014 Test



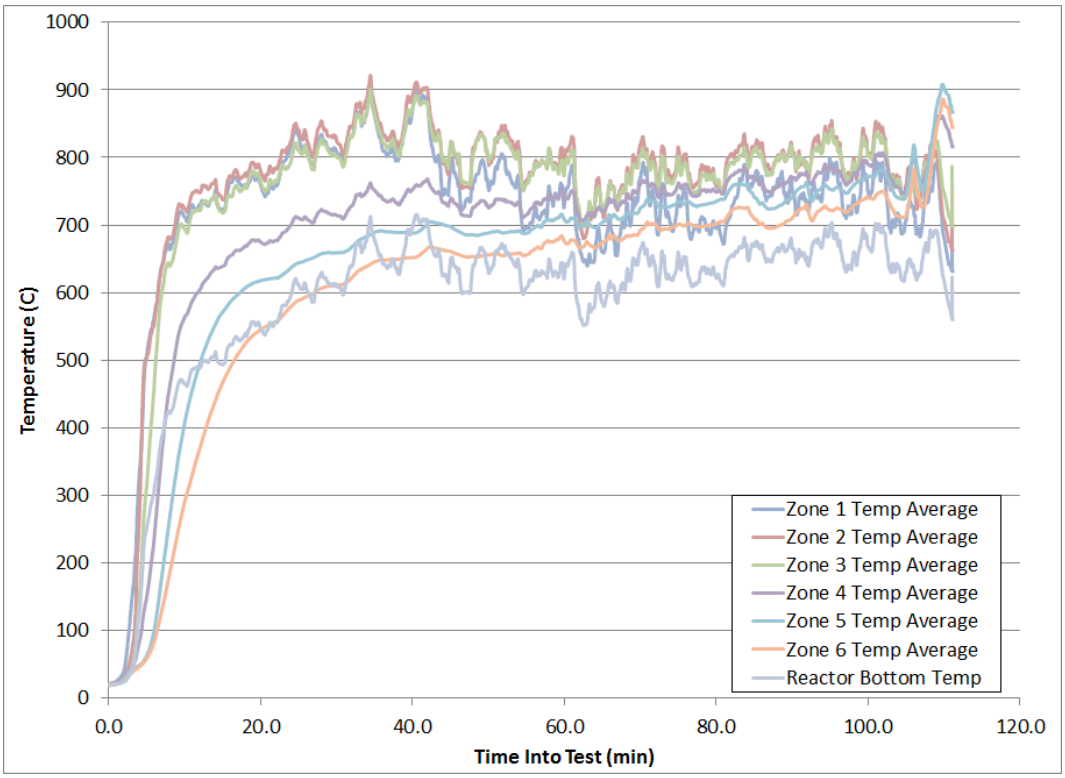


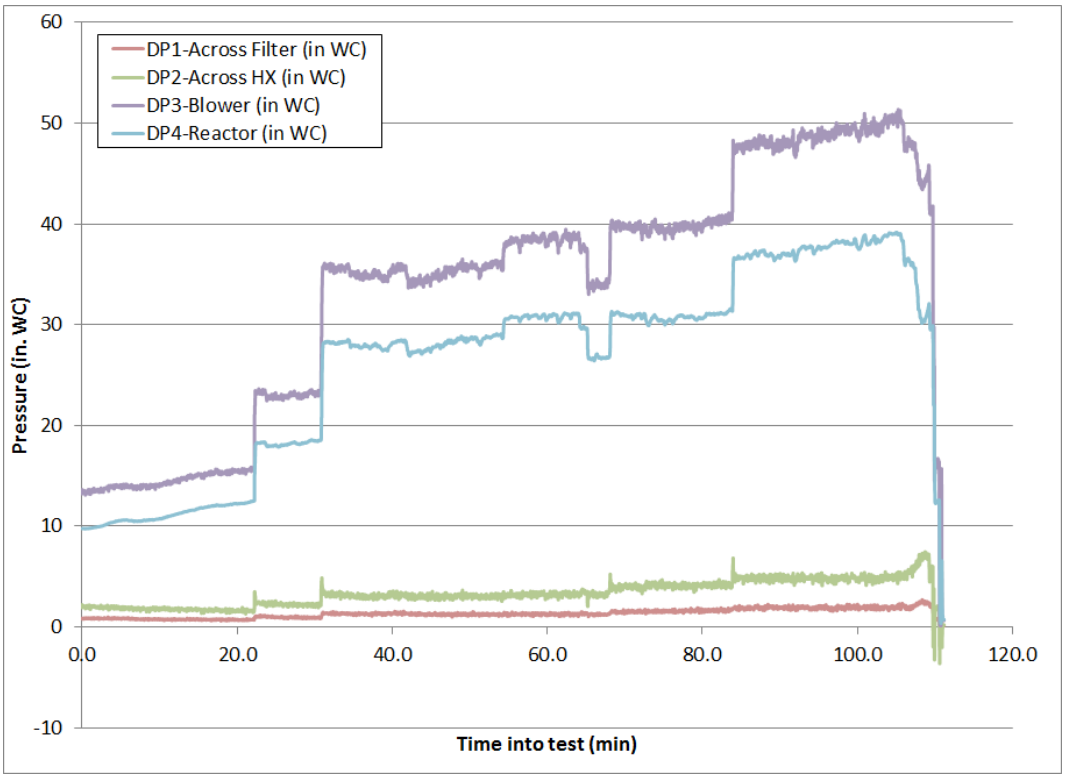
10/31/2014 Test





11/4/2014 Test





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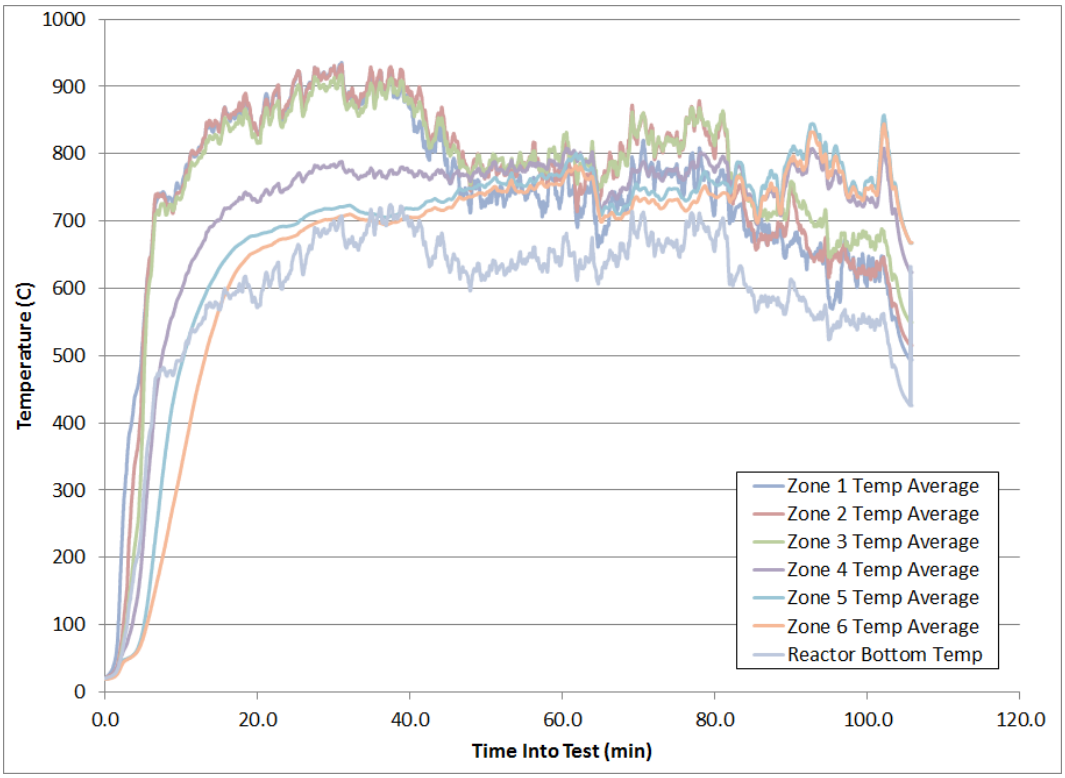

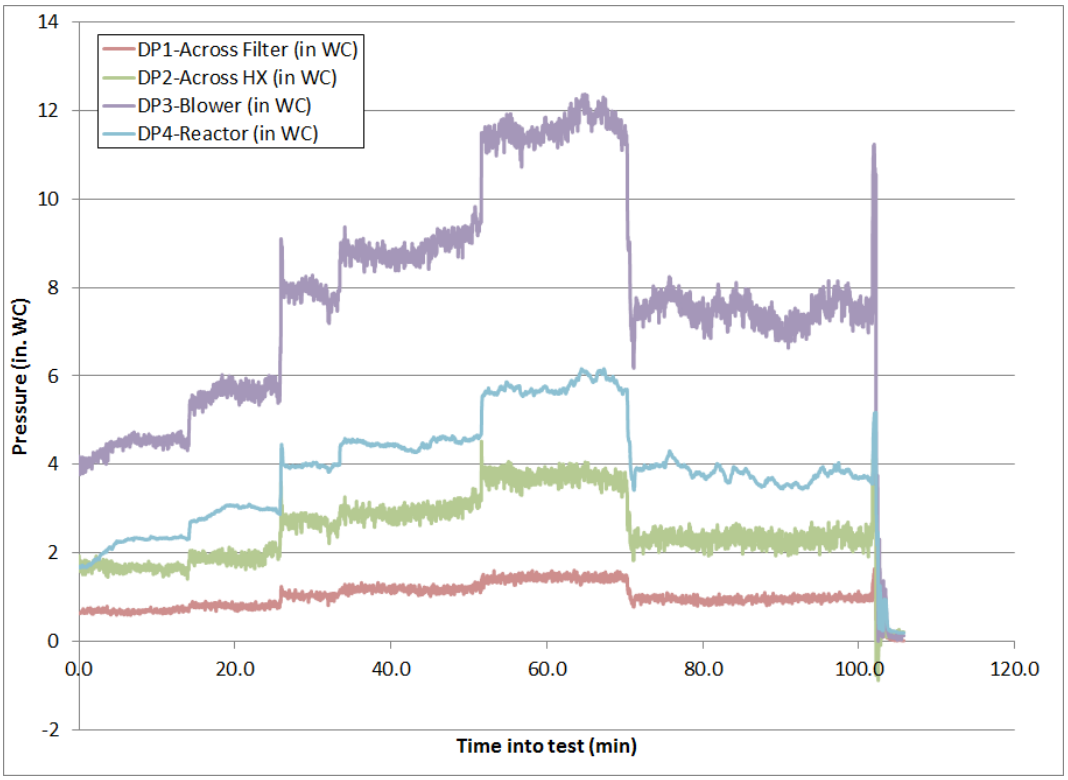

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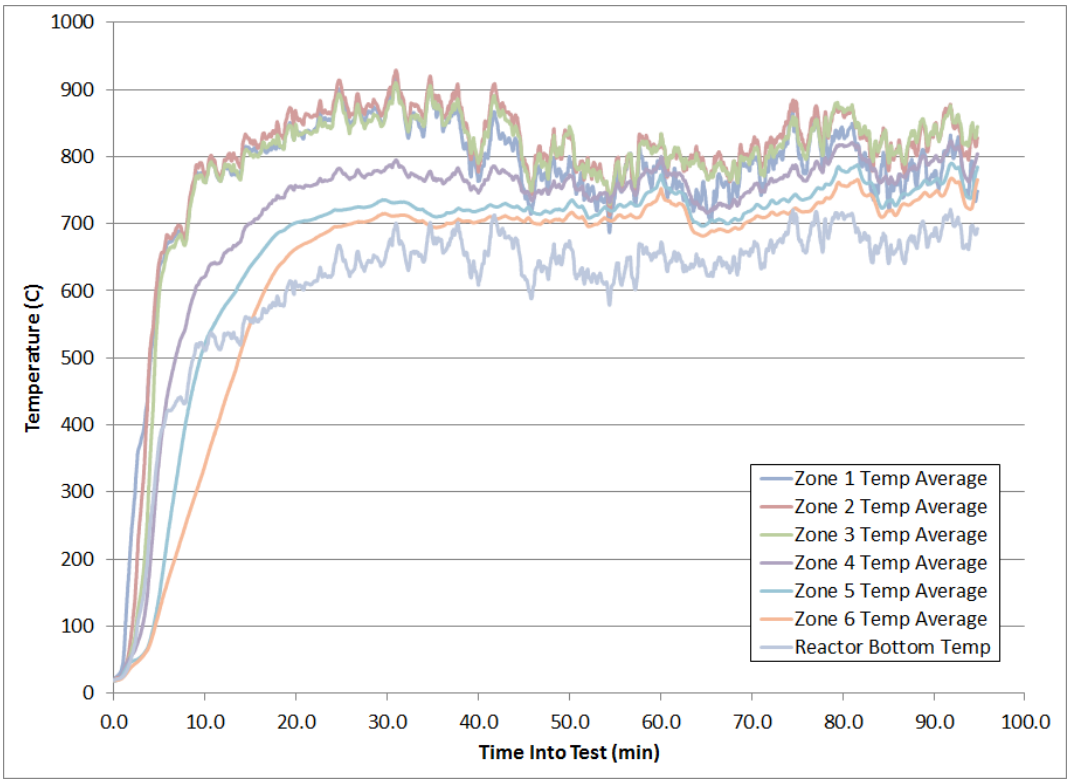

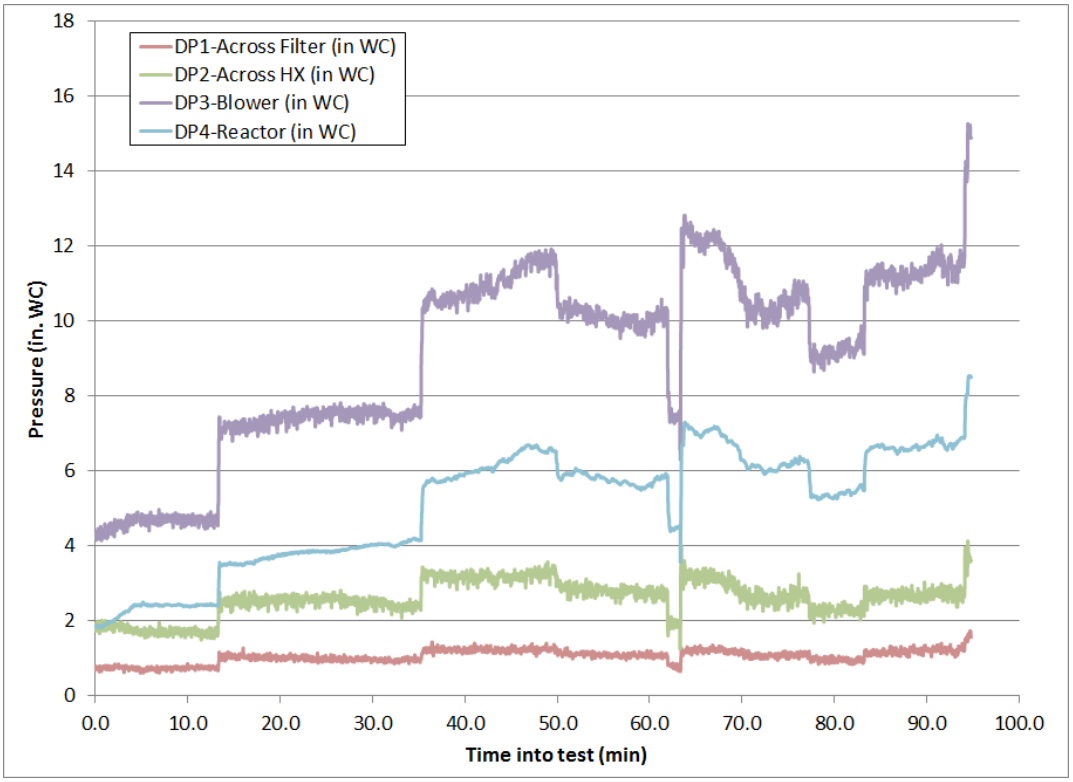

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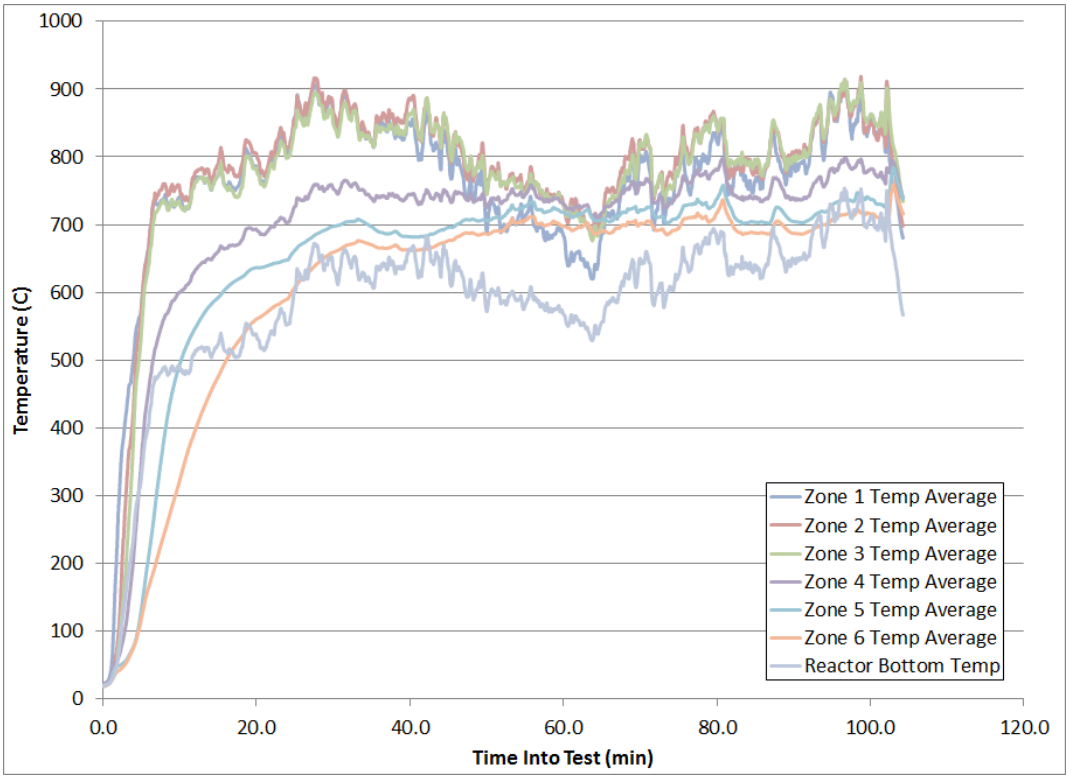

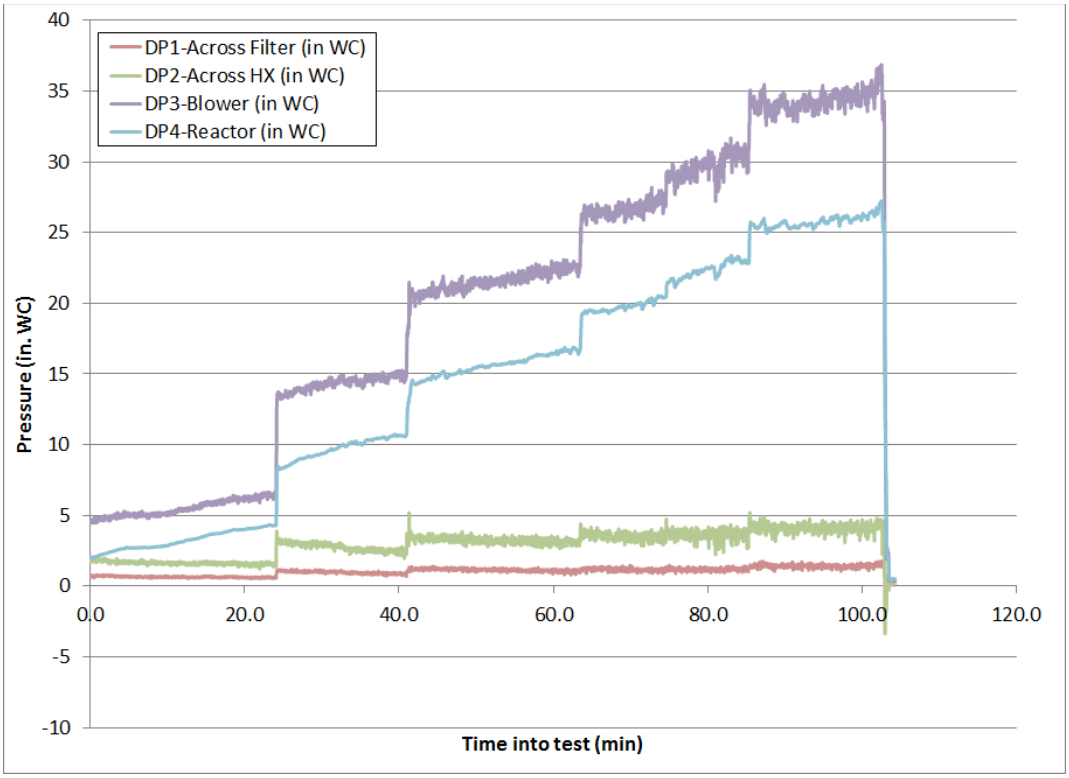

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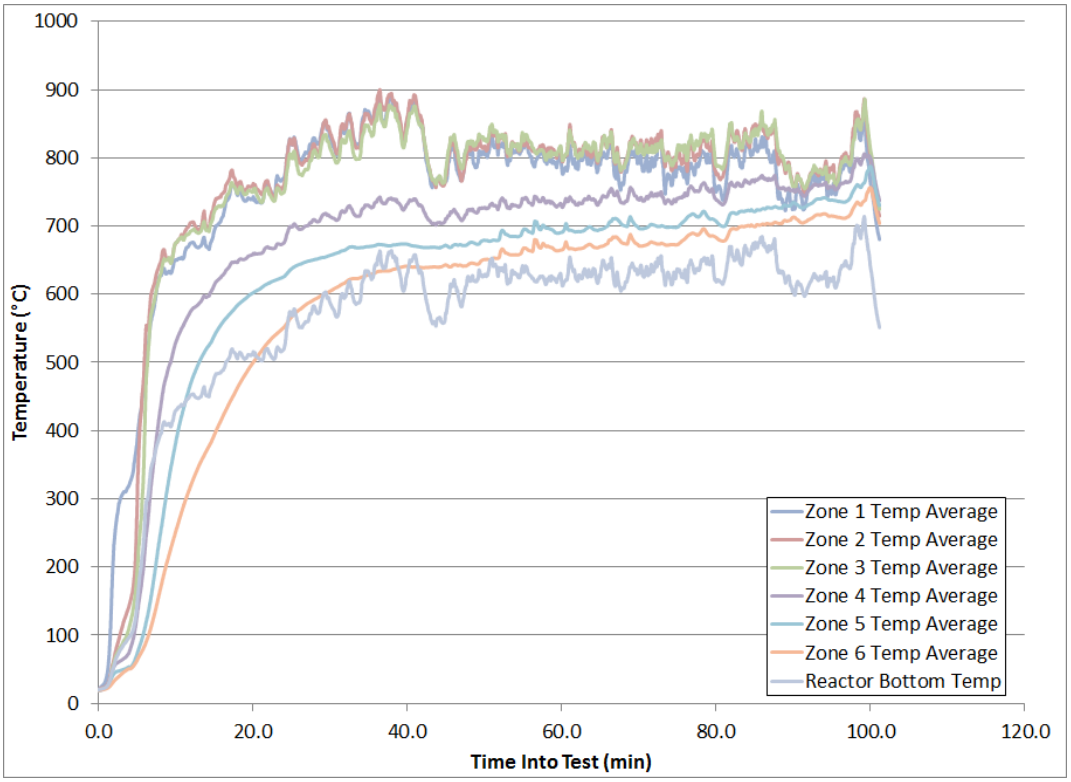

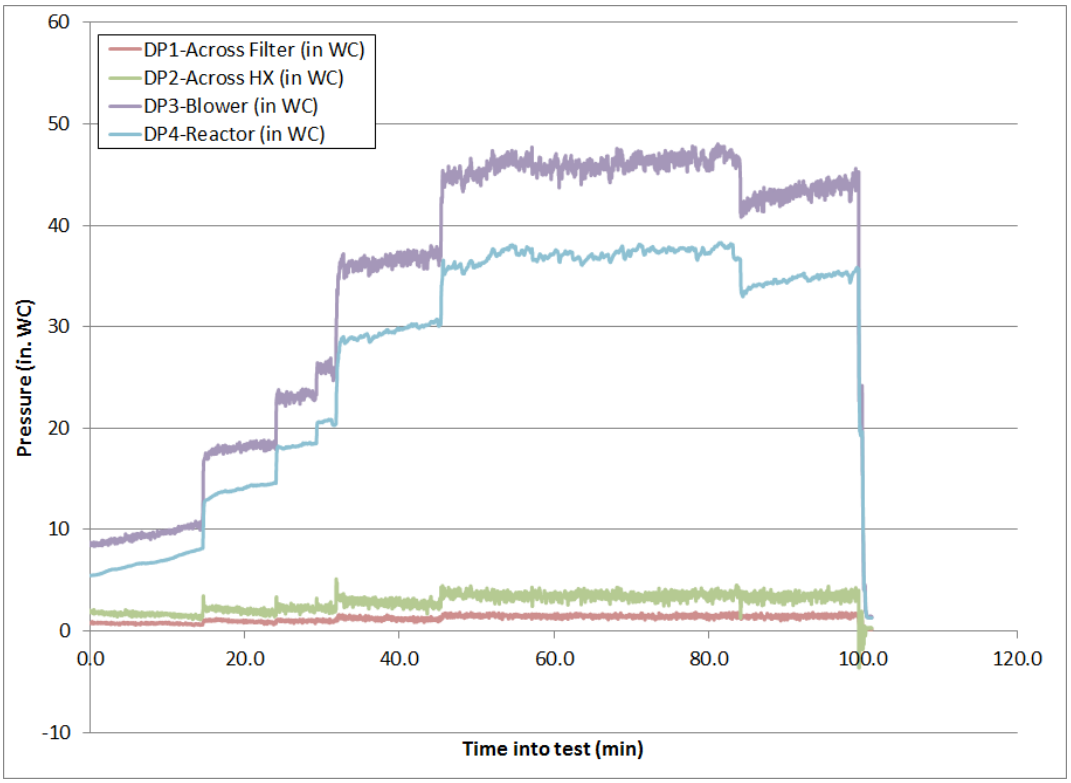

APPENDIX B: LIST OF SCIENTIFIC/TECHNICAL PUBLICATIONS

- Cushman, M., Sasa, L., Montella, D., Schlis, S., Reed, M., Gold, H., Young, M., Chase, S., Pittenger, B. *Shredded Waste Downdraft Gasification*; AICHE Paper Number 351629, March 2014.
- Reed, M., Cushman, M., Belcher, J., Schlis, S., and Sasa, L., *Shredded Waste Downdraft Gasifier for Overseas Waste to Energy Conversion*; EUEC 2015, February 2015.