Dry Coal Feed System and Multi-Element Injector Test Report

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Task 2. Injector and Feed System Development and Test

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ABSTRACT

Pratt & Whitney Rocketdyne (PWR) has developed an innovative gasifier concept that uses rocket engine technology to significantly improve gasifier performance, life, and cost compared to current state-of-the-art systems. One key feature of the PWR concept is the use of an ultra-dense phase feed system to provide dry coal to the gasifier's multi-element injector. This report describes the Phase 1 test results with such a feed system at 400-tons/day coal flow rates and 1,000 psia simulated gasifier operating pressures. This testing was conducted at the University of North Dakota's (UND's) Energy & Environmental Research Center (EERC) between June 2007 and October 2007. The feed system's layout, multi-element injector designs (using 1x6 and 1x18 flow splitters), test procedures, instrumentation and data acquisition requirements were provided in an earlier Test Plan Document.

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EXECUTIVE SUMMARY

This document describes the technical work related to testing the ultra-dense phase multi-element injector and feed system at the University of North Dakota's Energy and Environmental Research Center (EERC). A total of 15 short duration (nominally 4 minutes) ultra-dense phase feed system tests at 400-tons/day coal flow rates were conducted at gasifier simulation pressures ranging from 670 to 1,000 psia. Seven tests were conducted with the 1x6 multi-element injector -- four tests with Illinois #6 bituminous coal and three tests with Powder River Basin (PRB) sub-bituminous coal. Eight tests were conducted with the 1x18 multi-element injector -- five tests with Illinois #6 bituminous coal and three tests with PRB Basin sub-bituminous coal.

Overall, the coal feed system performed very well. All 15 tests were conducted without plugging of: (a) the feed line between the high pressure discharge tank (HPDT) and the conical gasifier chamber simulator, and (b) the pressure let-down discharge line between the conical gasifier chamber simulator and the atmospheric pressure cyclone/baghouse. In addition, the double ball-valve arrangement used at the HPDT's exit was able to complete the test series (approximately 40 actuations) without requiring any seal seats to be rebuilt.

The 1x6 split injector ran very well on both Illinois #6 bituminous and PRB sub-bituminous coal. The flow split non-uniformity was consistently measured at approximately 4.5 %RSD (relative standard deviation). However, the 1x18 two-tier split injector (at flow rates of 400-tons/day -- i.e., one-third rated flow capacity or 67% turn-down conditions) was unable to run with either coal under ultra-dense phase conditions (i.e., 55 vol% voids) without incurring solids flow stoppage in one-third to one-half of its injector elements. This solids flow stoppage produced unacceptably high flow split non-uniformities between 73 and 103 %RSD for the 67% turn-down condition. These flow split non-uniformities (with the 1x18 injector) were substantially improved to 10.6 %RSD (no injector element flow stoppage) by increasing the injector's inlet void fraction from 55 to 66 vol% during turn-down operation.

From this testing, a critical non-dimensional scaling parameter has been developed for ultra-dense phase feed multi-element injectors that is expected to produce good flow-split uniformity design guidance on future programs. With this scaling parameter, it is expected that flow splitting accuracies in the range of 2 %RSD can be achieved at full flow conditions and 4 %RSD at 50% turndown.

EXPERIMENTAL METHODS

The experimental methods used on this test program were extensively described in an earlier document -- Sprouse et al. (2006), *Dry Coal Feed System and Multi-Element Injector Test Plan* -- and need not be repeated here except for a few figures to provide internal continuity within this report. The EERC process flow diagram for the ultra-dense phase tests conducted during this effort is shown in Figure 1. The test system includes a 1,000-gal atmospheric coal storage silo that gravity drop feeds pulverized coal into a 700-gal high pressure discharge tank (HPDT) prior to test initiation. Once filled with pulverized coal, the valve at the top of the HPDT is closed and the tank pressurized to run conditions. Once pressurized, the ball valves at the exit of the HPDT are opened and coal is allowed to flow through the ultra-dense phase feed system (at static bed void fractions -- approximately 55 vol%) through the multi-element injector and into the conical gasifier simulation chamber. From the bottom of the injector's conical gasifier simulation chamber, the coal stream velocity is substantially increased and delivered to a multi-orifice cascade pressure let-down nozzle where the gas pressure is continuously reduced back to atmospheric conditions to increase the coal stream void fraction above 97 vol%. The cascade nozzle's exiting coal stream velocity is substantially reduced in order to match the downstream cyclone's inlet conditions for high particulate efficiency removal. Located downstream of the cyclone separator is a baghouse for absolute particle removal prior to venting the nitrogen gas into the environment. All solids removed by the cyclone and baghouse are subsequently returned to the 1,000-gal atmospheric silo for the subsequent batch mode test. It takes a little over 5 seconds to pressurize the conical gasifier simulation chamber to steady-state conditions at the nominal 400-tons/day coal flow rate once the HPDT's ball valves are opened.

The program's test-matrix is shown in Table 1. It consists of 12 tests at gasifier chamber pressures ranging from 675 to 1,000 psia with a nominal solids flow rate of 400 tons/day (9.26 lbm/sec) and a stream void fraction of 55 vol% (ultra-dense phase feed system conditions). Sprouse et al. (2006) indicated that some contingent testing may be possible at flow rates up to 1200-tons/day with additional funding. These higher flow rate tests will be conducted during the next phase of EERC testing. Two different pulverized coals were tested -- Illinois #6 bituminous and PRB sub-bituminous -- at standard industrial grind (nominally 70 wt% passing through 200 mesh, 74-μm opening, screen). The Illinois #6 coal was dried to approximately 2 wt% moisture and the PRB coal to approximately 10 wt%. The test plan indicated that PRB coal would be at approximately 15 wt% moisture, but Consol Energy Inc. was unable to meet this requirement at standard industrial grind conditions within their specialty mill.

Certainly, drying the PRB sub-bituminous coal to 10 wt% moisture requires more thermal energy and blanket gas flow consumption (per mass of coal fed) in the Consol Energy specialty mill than is typical of large-scale

industrial mills feeding pulverized coal fired boilers (PCFBs). Pulverized coal dried to lower moisture levels typically has lower cohesion coefficients and internal friction angles than higher moisture coal -- hence, it was somewhat easier to flow the PRB sub-bituminous than if it were at 15 wt%. However, the test results with both the Illinois #6 bituminous (at 2 wt% moisture) and the PRB sub-bituminous (at 10 wt% moisture) coals were consistent with PWR testing in the 1970-80's which included pulverized Montana Rosebud sub-bituminous coal (at 18 wt% moisture) and peat (at 9.6 and 15.5 wt%). Additional details regarding ultra-dense phase feeding of this high moisture pulverized peat are reported by Sprouse et al. (1980).

The test matrix also shows two multi-element injectors were used in this program: a single tier 1x6 element injector and a two-tier 1x18 element injector. At 400-tons/day, the 1x6 multi-element injector was operated under full-flow test conditions while the 1x18 multi-element injector was operated under 1/3 rated capacity (or 67% turndown). During testing, each injector was designed to operate with six Thermo Electron Corporation (2006) velocity sensors attached to their discharge orifices for the measurement of injector flow split non-uniformity.

The primary objectives for this program were to: (1) demonstrate plug free operation of a 400 tons/day ultra-dense phase feed system to 1,000 psia injector pressures using two different injector configurations and two different ranked coals, (2) obtain feed system pressure drop performance data for use in subsequent commercial designs, and (3) demonstrate uniform flow splitting within each of the two injectors' multi-elements to a relative standard deviation (RSD) of 2%.

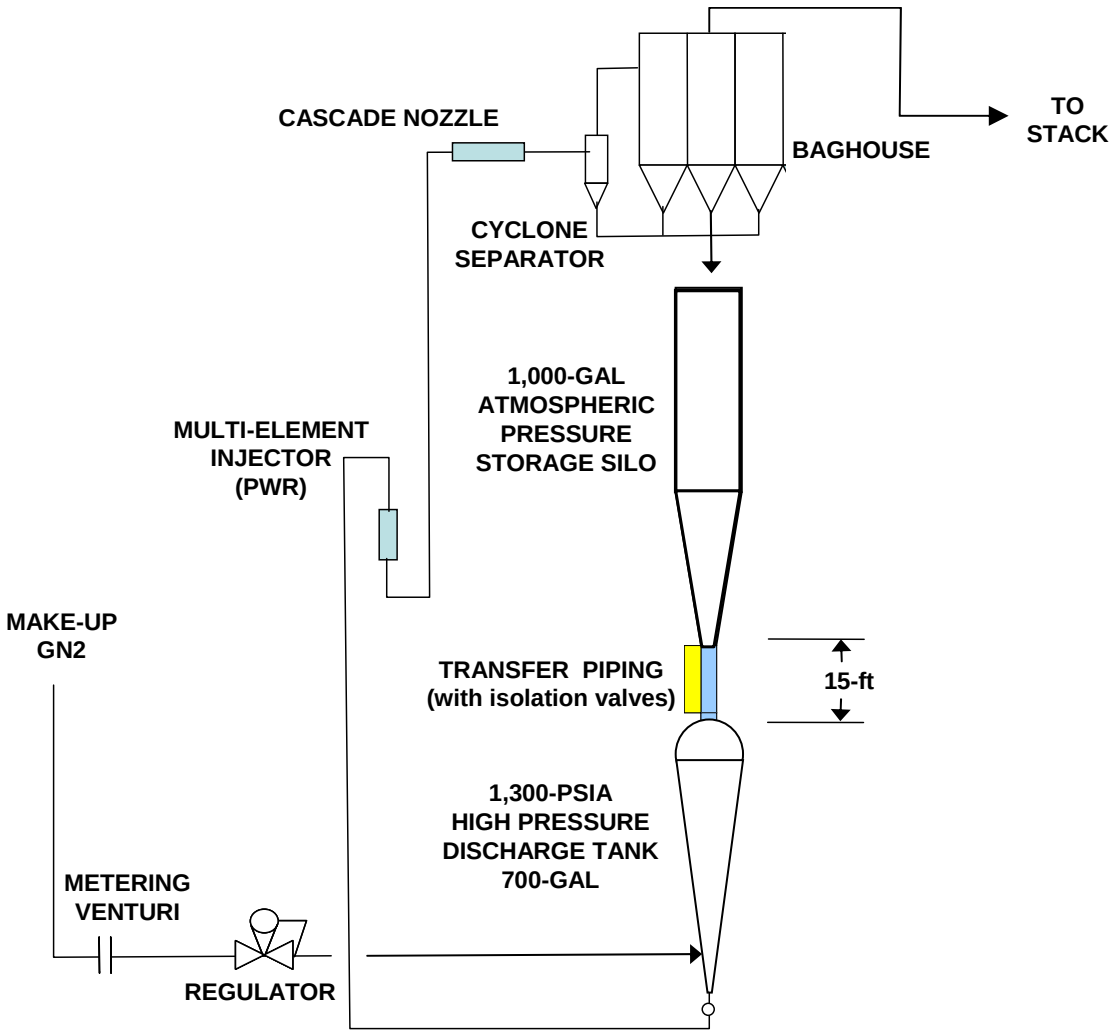

Figure 1. 400-Ton/Day Ultra-Dense Phase Feed System Flow Diagram at EERC

Table 1. Test Matrix

Input/Setup Run Conditions					Expected Test Results			
Test No.	Coal	Injector	Feed Line Pipe Size	HP-Tank Gas Pressure (Reg-2) (psia)	Coal Flow Rate Feed Line (lbm/sec)	Carrier GN2 Flow Rate Feed Line (lbm/sec)	Injector Cham Gas Pressure (PT-6L) (psia)	Void Fraction Feed Line (%)
1	Illinois #6	1 x 6	2-1/2"Sch160	725	9.26	0.465	675	55
2	Illinois #6	1 x 6	2-1/2"Sch160	850	9.26	0.545	800	55
3	Illinois #6	1 x 6	2-1/2"Sch160	1050	9.26	0.671	1000	55
4	Illinois #6	1 x 18	2-1/2"Sch160	695	9.26	0.440	675	55
5	Illinois #6	1 x 18	2-1/2"Sch160	820	9.26	0.520	800	55
6	Illinois #6	1 x 18	2-1/2"Sch160	1020	9.26	0.646	1000	55
7	PRB	1 x 6	2-1/2"Sch160	725	9.26	0.465	675	55
8	PRB	1 x 6	2-1/2"Sch160	850	9.26	0.545	800	55
9	PRB	1 x 6	2-1/2"Sch160	1050	9.26	0.671	1000	55
10	PRB	1 x 18	2-1/2"Sch160	695	9.26	0.440	675	55
11	PRB	1 x 18	2-1/2"Sch160	820	9.26	0.520	800	55
12	PRB	1 x 18	2-1/2"Sch160	1020	9.26	0.646	1000	55

RESULTS AND DISCUSSION

A summary of the 15 tests (4-minutes duration each) conducted at EERC from June through October 2007 are shown in Table 2 below. This table gives the assigned facility test number, the date of the test, the type of coal tested, the feed system line size, and the injector's multi-element flow splitter configuration together with tank pressures, solids and gas flow rates through the feed line, and important injector flow splitter performance information. As mentioned above, both coals, as tested, were pulverized to standard industrial grind by Consol Energy Inc. (South Park, PA) -- i.e., 70 wt% passing thru 200 mesh (74-μm opening) screen. Both coals were supplied from Peabody Energy Inc. owned mines in the states of Illinois and Wyoming. The Illinois #6 bituminous coal as tested was approximately 2 wt% moisture and the Powder River Basin coal was approximately 10 wt% moisture. Neither coal showed any cohesive tendency.

The as-built EERC test facility, as it existed during the June through October 2007 campaign, is shown in Figure 2. The foreground shows both the 1,000-gal atmospheric coal storage silo (mounted on the 5th floor) and the 700-gal HPDT (mounted on the 2nd floor). The patent pending cascade pressure letdown nozzle and cyclone subsystem are mounted on the 6th floor and are shown further in a close up view in Figure 3. The gas discharge from the top of the cyclone is directed to a standard baghouse while solids are transferred from the bottom of the cyclone through a standard rotary air lock. The cascade nozzle is located behind the cyclone in the Figure 3 view.

The two as-built multi-element injectors are shown in Figure 4 as they were mounted on the 2nd floor conical gasifier simulation chamber. The conical chamber is located directly behind the 700-gal HPDT in Figure 2. Both injectors incorporated six Thermo Electron Corp. (2006) velocity sensors on their discharge orifices for measuring flow non-uniformity as outlined in the test plan by Sprouse et al. (2006). In Figure 4 they are seen as the short blue spool sections just above the conical gasifier simulation chamber's upper flange. Hence, all discharge orifices on the 400-tons/day 1x6 injector are instrumented while only one-third of the discharge orifices on the 1200-tons/day 1x18 injector are instrumented with sensors for determining flow non-uniformity. As seen in Table 2 all testing with the 1200-tons/day 1x18 injector was conducted at one-third of rated flow (67% turn-down).

Table 2. Test Results Summary

Test No.	Test Date	Coal Type	Injector Splitter	Feed Line Pipe Size	HPDT Gas Pressure (psia)	Conical Gasifier Pressure (psia)	Coal Flow Rate Feed Line (lbm/sec)	Carrier GN2 Flow Rate Feed Line (lbm/sec)	Void Fraction Feed Line (%)	Injector Bingham Stress No.	Injector Splitting Flow Non-Uniformity (%RSD)	Notes
2007-01	6/12/2007	Ill #6	1 x 6	2-1/2"Sch160	730	661	9.19	0.441	55	4.43	4.5	
2007-02	6/13/2007	Ill #6	1 x 6	2-1/2"Sch160	840	782	9.53	0.525	55	4.60	4.3	
2007-03	6/19/2007	Ill #6	1 x 6	2-1/2"Sch160	1048	968	10.4	0.715	55	5.01	49.0	FOD in system. No flow thru one injector orifice.
2007-04	6/21/2007	Ill #6	1 x 6	2-1/2"Sch160	1048	974	10.5	0.722	55	5.06	4.5	Re-run of Test No. 2007-03.
2007-05	7/3/2007	Ill #6	1 x 18	2-1/2"Sch160	1055	987	10.2	0.719	55	0.78	72.8	No flow thru one-third of injector orifices.
2007-06	7/10/2007	Ill #6	1 x 18	2-1/2"Sch160	849	781	9.68	0.549	55	0.72	72.8	No flow thru one-third of injector orifices.
2007-07	7/11/2007	Ill #6	1 x 18	2-1/2"Sch160	850	777	9.15	0.521	55	0.68	103.0	No flow thru one-half of injector orifices
2007-08	7/13/2007	Ill #6	1 x 18	2-1/2"Sch160	732	669	8.46	0.414	55	0.62	103.0	No flow thru one-half of injector orifices
2007-09	7/31/2007	Ill #6	1 x 18	2-1/2"Sch160	732	665	9.35	0.458	55	0.69	103.0	Corrected factory switch error in velocity probes. No flow thru one-half of injector orifices.
2007-10	8/9/2007	PRB	1 x 6	2-1/2"Sch160	736	685	9.29	0.439	54	4.48	4.5	
2007-11	8/10/2007	PRB	1 x 6	2-1/2"Sch160	858	799	9.90	0.545	54	4.77	4.5	
2007-12	8/21/2007	PRB	1 x 6	2-1/2"Sch160	1061	988	11.7	0.797	54	5.64	4.5	
2007-13	10/3/2007	PRB	1 x 18	2-1/2"Sch160	1056	945	10.5	0.740	54	0.78	72.8	No flow thru one-third of injector orifices.
2007-14	10/9/2007	PRB	1 x 18	2-1/2"Sch160	789	748	8.81	0.689	65	NA[1]	10.6	Pneumatic-phase flow.
2007-15	10/16/2007	PRB	1 x 18	2-1/2"Sch160	1082	1026	10.5	0.947	61	NA[1]	46.0	Pneumatic-phase flow. No flow thru one-sixth of injector orifices.

[1] Not Applicable (NA) for this test since injector flow was in a pneumatic rheological state rather than the ultra-dense phase Bingham plastic state.

TOWER 5TH FLOOR SOUTH VIEW

TOWER GROUND FLOOR SOUTH VIEW

Figure 2. EERC Six-Story Tower Test Facility

6TH FLOOR NORTH VIEW

Figure 3. Cascade Nozzle and Cyclone Separator

1x6 400-Ton/Day Injector

1x18 1200-Ton/Day Injector

Figure 4. As-Built Multi-Element Injectors on EERC Test Stand

1.0 DATA COLLECTION

General data on coal flow rate, transport gas flow rate, gas pressures, and injector velocities (among other variables) were collected following the procedures outlined in the test plan by Sprouse et al. (2006). The coal flow rate was first determined from load cell weight measurements on the HPDT mounting fixtures. A typical load cell time-trace is shown in Figure 5. Using the continuity mass balance formula found in this figure for a HPDT at constant gas pressure, the coal's mass flow rate exiting the HPDT can be readily determined. This mass coal flow rate together with the facility's measured gas flow rates for the HPDT pressurization gas (FT1), baghouse exit (FE1), and coal's carrier transport N2-gas were then reported in near-real time during the test as shown in Figure 6. This figure also shows a "rat-holing" condition that occurred at the end of a few tests where the coal level in the HPDT was allowed to get too close to the tank's exit. During "rat-holing" the coal flow rate rapidly drops while its carrier transport gas flow rate rapidly increases. One should note that the test which produced the Figure 5 load cell time-trace did not experience any "rat-holing."

Typical gas static pressure traces are shown in Figure 7 at various locations within the feed and discharge flow system. Numerous gas pressure drops were also measured with delta-P transducers and their typical time-traces are shown in Figure 8. Most of the pressure tap locations are filtered to prevent plugging with coal particles during operation. This filtering produces slight time delays between process piping static gas pressures and their related transducer pressure. In Figure 7, the important static gas pressure traces are those for the HPDT (PT3) and the conical gasifier simulation chamber (PT5). The time-trace of the differential gas pressure transducer (DPT6) -- that directly measured the static gas pressure between these two locations -- is shown in Figure 8 along with other delta-pressure transducer outputs.

Finally, typical solids velocity traces from the Themo Electron Corp. (now ThermoFisher Scientific Inc.) velocimeters located on the multi-element injector's exit nozzles are shown in Figure 9. Only one Model 2109 correlator was used to read the voltage output signals from all six velocimeters. A rotary switch was installed between the Model 2109 correlator and all six sensors so that each sensor's output was sequentially recorded over a 10 second interval within a 60-second cyclic period. Thus Figure 9 contains two time-traces. The first trace is the sensor number trace whose value is read on the right side of the figure. This traces gives the sensor number (either 1, 2, 3, 4, 5, or 6) whose velocity output is being recorded at a particular time. The second trace gives the actual velocity of the probe being monitored. A nominal 2 to 3 second delay was observed from the time a sensor was switched on before that sensor's actual reading is recorded. During this 2 to 3 second switching interval, an average velocity output between this sensor and its predecessor is displayed.

Before-test and after-test measurements were completed on the Illinois #6 bituminous and the PRB sub-bituminous coals for moisture content, particle size distribution, bulk density and particle density. These results are presented in Table 3. They are consistent will the values reported initially by Consol Energy following their pulverization and drying operation prior to shipment to EERC. The moisture content of the PRB sub-bituminous coal was closer to 10 wt% than the 8 wt% originally reported by Consol. All coal distributions were found to be somewhat less than 70 wt% passing thru 200 mesh screen (about 65 wt% for Illinois #6 bituminous and 56 wt% for PRB sub-bituminous). It should be noted that the particle size distributions tended to increase for both coals during operation. The more dramatic change observed for the PRB coal was likely due to the fact that the finer coal particles, which passed through the cyclone and collected in the baghouse, were not returned to the atmospheric silo during the course of six test periods and were not represented in the final coal analyses. During tests with the Illinois No. 6 coal, solids recovered from the baghouse were reloaded into the silo after Test No. 2007-03 and Test No. 2007-05. Therefore, observed changes in coal particle size are likely the result of size segregation through the cyclone and material handling.

Table 3. Results of Illinois No. 6 and Powder River Basin Coal Analyses

	Illinois No. 6 Coal Initially Loaded	Illinois No. 6 Coal Unloaded	PRB Coal Initially Loaded	PRB Coal Unloaded
Test Numbers	2007-01 through 2007-09		2007-10 through 2007-15	
Moisture, wt%	0.42	1.38	9.81	9.78
Particle Density, lb/ft^3	87.3	86.1	86.1	86.1
Bulk Density, lb/ft^3	41.8	41.6	37.5	44.5
Sieve Analysis				
Screen Mesh Size	wt% Retained			
100	6.7	6.3	12.6	13.0
140	10.8	11.3	14.0	23.9
200	15.5	19.6	14.5	10.7
230	39.3	38.3	26.6	45.4
270	15.4	5.9	20.3	5.1
325	0.9	5.3	1.0	0.5
Pan	11.4	13.2	11.0	1.4
Total %	100.0	100.0	100.0	100.0

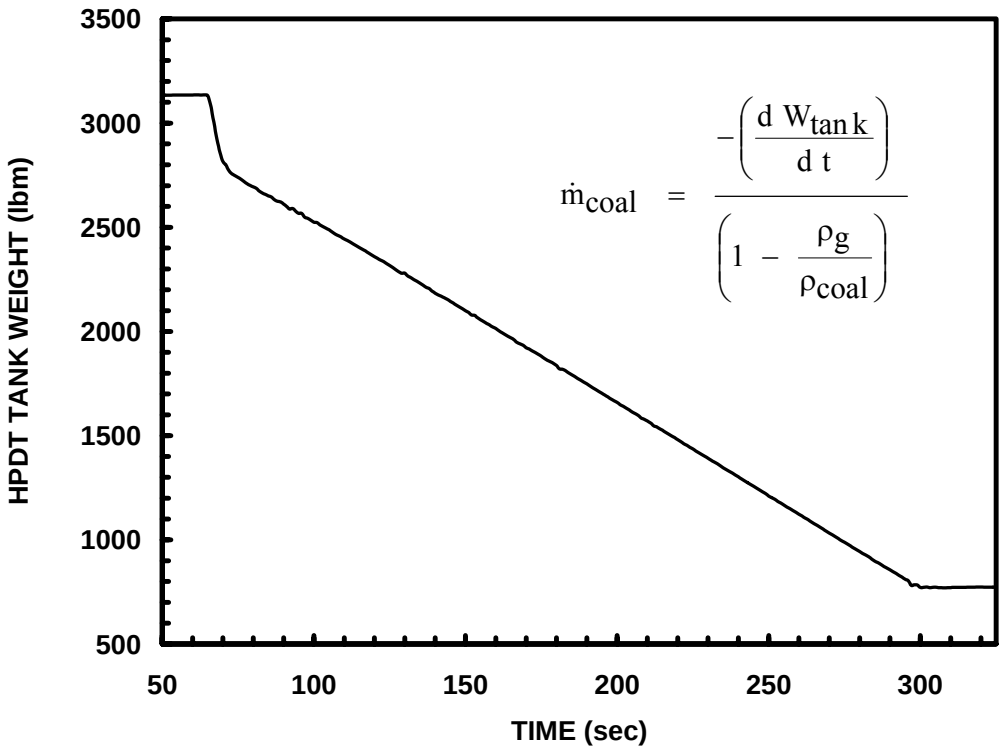

Figure 5. HPDT Weight Time Trace During Test -- Typical

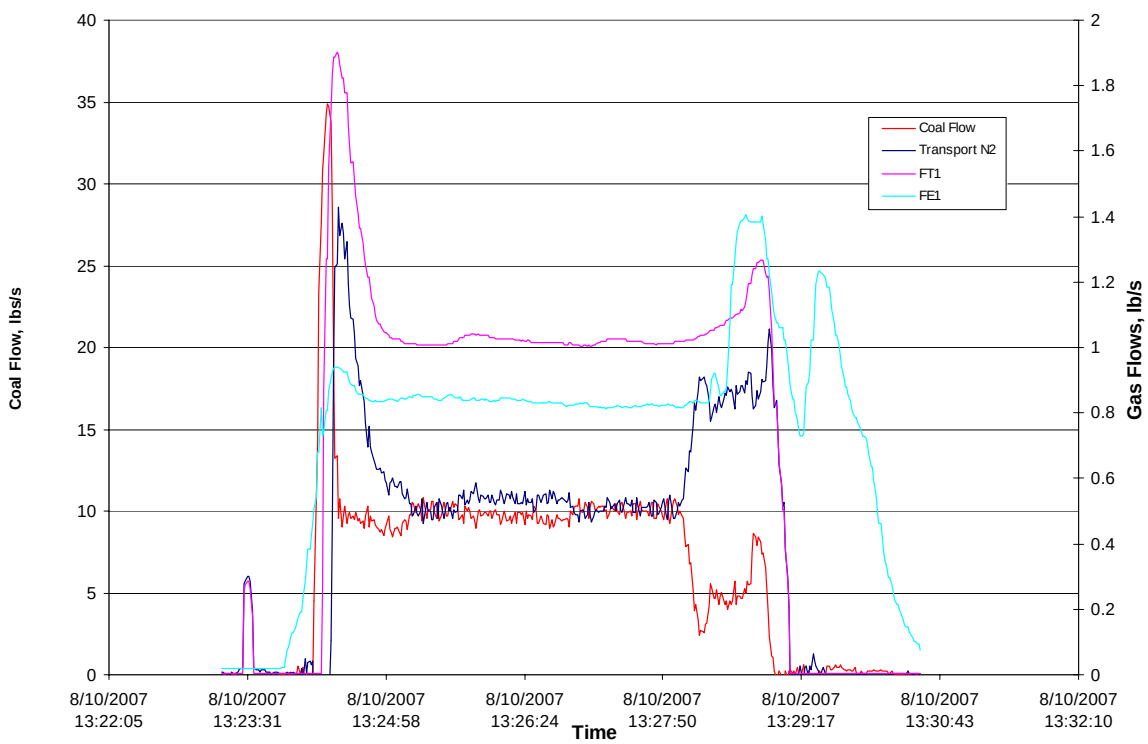

Figure 6. Coal and Gas Mass Flow Rates -- Typical

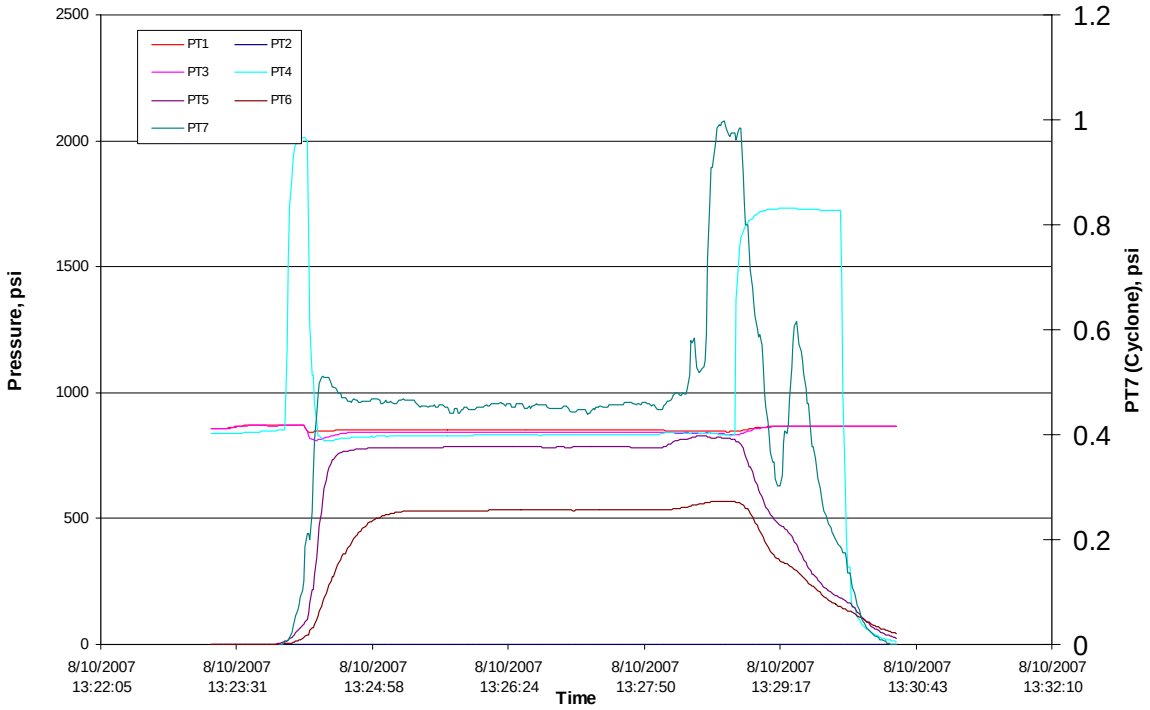

Figure 7. Gas Static Pressure Traces -- Typical

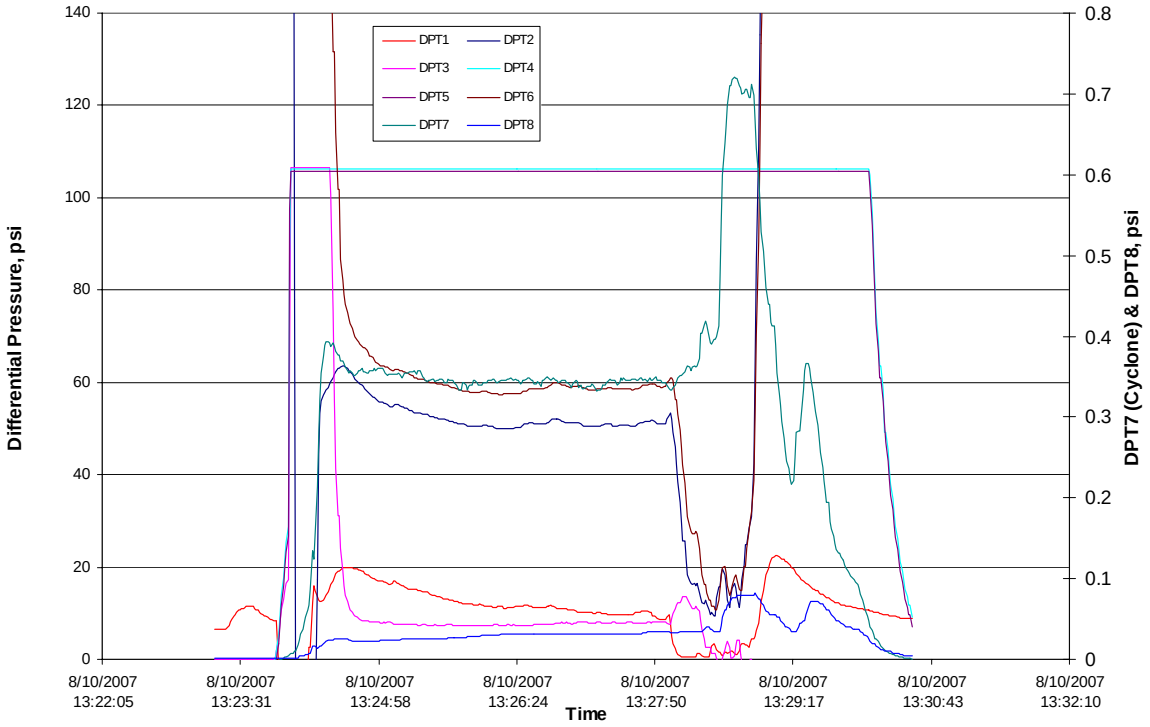

Figure 8. Gas Differential-Pressure Drop Traces -- Typical

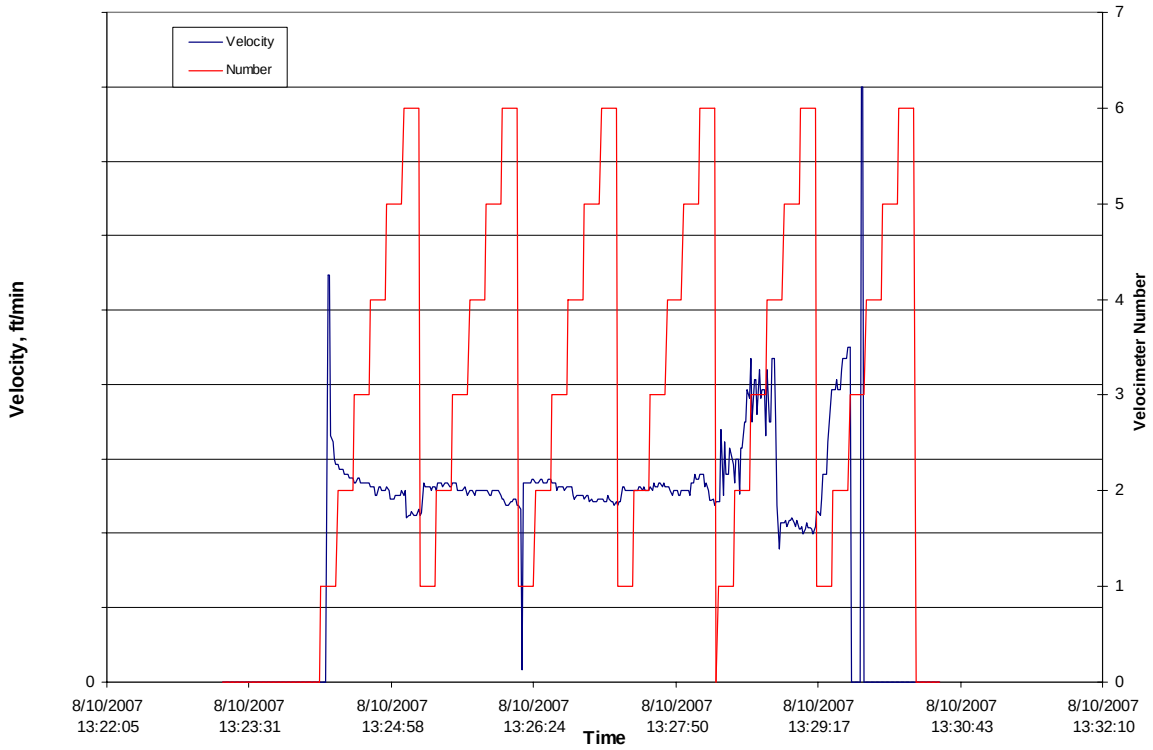

Figure 9. Splitter Orifice Velocity Time Traces -- Typical

2.0 FEED SYSTEM PERFORMANCE

The overall ultra-dense phase feed system performed as expected during the 15 batch mode tests (the first 13 under ultra-dense phase flow conditions). The pressure drops and pulverized coal flow rates reported in Table 2 for the 2-1/2"Sch.160 piping system (between the HPDT and the injector) scaled very well with the analytical methodology provided by Sprouse and Schuman (1983 and 1986) which was used to correlate ultra-dense phase flow testing in much smaller tubing systems. This feed system was operated in batch mode over a total solids flow period of nearly 1.5 hours with 33 pressurization/depressurization start/stop cycles. Post test dimensional measurements of the piping system's interior surfaces and walls showed no measurable erosion. This was a very favorable result since, at the start of each test, the gas flow exiting the HPDT is running at choked flow (Mach 1) conditions until all the downstream piping reaches steady-state operation (usually in about 15 to 25 seconds).

The HPDT's dual ball valve arrangement was also a significant improvement over previous testing (from the 1970-80's) in that the assembly was leak tight following all 33 actuations -- i.e., none of the seals ever needed to be rebuilt. Previously, PWR experience with a single ball valve arrangement required seal and seat replacement overhauls every 9 to 12 actuations.

The larger 2-1/2"Sch.160 feed system piping used in this testing was also an advantage over the previous PWR ultra-dense phase systems from the 1970-80's since no EERC feed system test was prematurely terminated due to solids flow bridging in lines or by foreign object debris (FOD) plugging. This is very important for ultra-dense phase feed systems which require major line repair activities whenever a feed line becomes plugged with fine granular powders. Depending upon the level of solids compaction, these repairs sometimes require complete line sections to be removed and the plugged solids machine-drilled for removal.

3.0 MULTI-ELEMENT INJECTOR PERFORMANCE

From Table 2 above, it can be seen that neither multi-element injector was able to obtain measured flow-splitter non-uniformities below the 2 %RSD program goal. In fact, the 1x18 multi-element injector was unable to operate under ultra-dense phase flow conditions without flow stoppage in one-third to one-half of its orifices at its 67% solids turndown flow rate of 400-tons/day. On the other hand, the 1x6 multi-element injector (rated at 400-tons/day for full flow) consistently produced splitter flow non-uniformities of 4.5 %RSD for both Illinois #6 bituminous and PRB sub-bituminous pulverized coal.

It should be noted here that the 2 %RSD goal was based on earlier 1980's PWR testing with a much smaller 1x3 multi-element splitter -- see, Falk (1982) and Combs (1982). This testing produced splitter non-uniformities at approximately 1.2 %RSD where flow splitting was measured by solids capture in pressurized downstream tanks. Based upon this discrepancy, the following non-dimensional analysis is provided to understand how to improve splitting performance in future multi-element designs.

Coal feeding in the ultra-dense phase condition is known to cause plugging if sufficient pressure drop is not provided across a given feed line -- see, e.g., Sprouse and Schuman (1983 and 1986) for the analytical understanding behind this phenomenon. The rheology of such ultra-dense phase solids can also be characterized in the simple terms of a Bingham plastic -- see, e.g., Perry and Chilton (1973) -- which uses the parameters of yield stress, τ_y, and coefficient of rigidity, η_{rig}, to describe the materials resistance to applied stresses. Using the ultra-dense phase solids flow data of Sprouse and Schuman (1983); Sprouse (2005) reports that this data could have been alternately modeled with a yield stress, τ_y, of effectively 11.3 Pascal (Pa), and a coefficient of rigidity, η_{rig}, of 10.0 centipoise (cp).

Applying Bingham plastic theory -- Perry and Chilton (1973) -- to the analysis of multi-element injectors, one can define a non-dimensional Bingham Stress Number, Bh, as:

$$Bh \equiv \frac{8 \ v \ \eta_{rig}}{D \ \tau_y} \tag{1}$$

where the variable v is the velocity of the ultra-dense phase flow within the multi-element injector, and D is the inside diameter of the multi-element injector's largest parallel flow passages. Bingham plastic theory shows that this number is approximately equal to the relative stress margin between the shearing stresses on the injector's walls , τ_w , and the Bingham yield stress. That is:

$$Bh \approx \frac{\left(\tau_w - \tau_y \right)}{\tau_y} \tag{2}$$

In order to avoid flow stoppages within various multi-element injector orifices, one needs to ensure that the wall shearing stress, τ_w , is sufficiently above the fluid's yield stress, τ_y. Preventing flow stoppages within these multi-element injectors is the key to achieving good flow splitting uniformity (or alternately speaking -- low flow non-uniformities as expressed by the standard deviation of the flow rates issuing from the injector's multiple orifices). Using the test results from this program (as reported in Table 2 -- second and third columns from the left) and those from Falk (1982) with the Bingham plastics parameters from Sprouse (2005), a plot of measured splitter flow non-uniformities, s, versus Bingham Stress numbers, Bh, can be given as shown in Figure 10 for the multi-element injectors tested by PWR to date.

As seen in Figure 10, higher Bingham stress numbers, Bh, produce lower splitter flow non-uniformities, s. Furthermore, there appears to be a critical Bingham stress number somewhere between 1.0 and 3.0 that an injector designer needs to stay above to prevent drastic increases in flow non-uniformities. It is recommended that the EERC facility modifications -- required for testing the 1x18 multi-element injector at its rated 1,200-tons/day flow rate -- be made in order to further explore this critical Bingham region. Increases in the solids flow rate to 1,200-tons/day will produce Bingham Stress numbers at approximately 2.3.

One can see that the higher Bh numbers (and hence lower flow non-uniformities) are primarily achieved by increasing the solids velocity inside the injector or decreasing the diameters of its passages. Achieving better flow split uniformity by increasing the solids velocity, v, within the injector comes at the expense of higher erosion rates within this component. Likewise, decreasing the

multi-element injector's flow passage diameters, D, to get better split uniformities comes at the increased risk of plugging an orifice by FOD -- as experienced in Test 2007-03 of this program with an extraneous rubber washer. Furthermore, PWR found in earlier 1970-80's testing that the Bingham yield stress, τ_y, is not constant at tube inside diameters below 0.180-in. when flowing standard industrial grind coals. Here, the Bingham yield stress, τ_y, increases exponentially with decreasing inside diameters thus pushing the Bh number to very low values and rapid plugging.

Due to the repeated problems incurred with the 1x18 multi-element injector at its 67% turn-down condition, DOE approval was given to run the last two tests (Tests 2007-14 and 2007-15) in a pneumatic flow condition rather than in ultra-dense phase flow. This was achieved by introducing a small nitrogen gas flow through the ball valve purge line just downstream of the HPDT during the test. As seen in Table 2 this additional nitrogen gas flow rate increased the flow stream's void fraction to 61 vol% on Test 2007-15 and 65 vol% on Test 2007-14 from the nominal ultra-dense phase value of 54 vol% with PRB coal. As seen in Table 2, flow stoppage was still experienced in 1/6 of the multi-element injector's 18 discharge orifices at 61 vol% voids but was completely flowing at 65 vol% voids with a splitter flow non-uniformity of approximately 10.6 %RSD. Certainly, increasing the feed system's void fraction at the injector inlet is one method of lowering the splitter flow non-uniformity when feeding coals in ultra-dense phase at low Bh numbers. Although a pneumatic flow non-uniformity of 10.6 %RSD would usually be considered high for successful compact gasifier operation; when operating at 67% turn-down throttling, this value is certainly much better than 73 %RSD under ultra-dense phase conditions.

The use of a small gas bleed upstream of the injector to prevent partial flow stoppage at low Bingham Stress numbers, Bh, is a reasonable modification to the overall PWR dry solids pump and feed system layout for increased gasifier turndown capability. The bleed gas is introduced through normal screened pressure taps within the feed system piping so that additional hardware is not required. Depending upon the depth of turndown and the volume capacity of the HPDT, the dry solids pump can be operated either at slower speed or intermittently to keep the HPDT and downstream feed system functional with the injector gas bleed at reasonable injector flow splitting non-uniformities.

Use of the six Thermo Electron velocity sensors was a major cost reduction breakthrough in the measurement of multi-element injector flow splitting non-uniformity. In the past, numerous high pressure vessels had to be constructed and connected to each of the injector's discharge orifice flow streams for capturing the total solids weight over a given period of time for subsequent measurement. The cost of these high pressure vessels would have been prohibitive for a 6-element (or more) injector at flow rates above 400-tons/day. Although the cost of these probes was reasonable, it did take some time and manpower to figure out and correct a bias problem with these sensors over the

course of the program. After significant diagnostic activity using oscilloscopes to get direct output voltage time-traces on each pair of electrodes within the sensor, it was determined that two switches on the probe's integrated circuit (IC) boards were factory set to the wrong position. Since descriptions of the sensor's IC boards were not included in the Thermo Electron operating manuals, it took a few weeks to isolate the problem while working with Thermo Electron's instrumentation engineers.

One should note that measuring splitter flow non-uniformities below 2 %RSD with the current set of Thermo Electron velocity sensors at EERC may be problematic. Initial flow calibration of these velocity sensors (where they were all connected in series) produced a combined random uncertainty of 1.5 %RSD.

Finally, no erosion was seen (after approximately 1.5 hours of total testing) in either the 1x6 (400-tons/day) injector or the 1x18 (1200-tons/day) injector. All internal splitter elements appeared to be in pristine condition. This result was not unexpected since low velocity bulk solids water-slurry systems have been known to operate for thousands of hours without experiencing significant erosion.

Tip inserts were installed on all discharge orifices of the 1x18 injector for Test 2007-13 in an attempt to increase the pressure drop across the injector. Although the pressure drop was slightly increased, the flow splitting non-uniformity was left unchanged from the earlier tests with Illinois #6 coal. Hence, these tips were subsequently removed prior to the start of Test 2007-14.

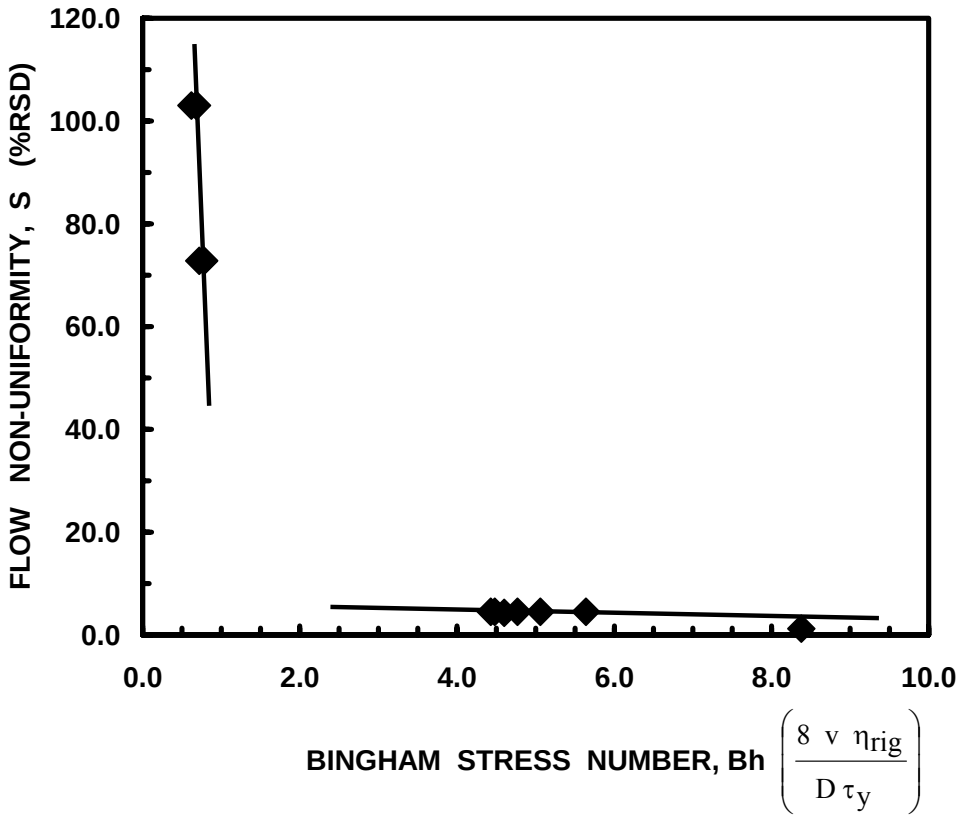

Figure 10. Multi-Element Splitter Non-Uniformity as a Function of the Bingham Stress Number

4.0 DISCHARGE PIPING SYSTEM

The discharge piping downstream of the conical gasifier simulation chamber operated as expected for all tests. This piping arrangement also includes the patent pending cascade nozzle shown in Figure 3. The discharge piping system is designed to keep solids velocities rather low as the solids flow stream expands from ultra-dense phase conditions at 55 vol% void fraction and 1,000 psia gas pressure to highly dilute phase pneumatic conditions at 99 vol% void fractions and 14.7 psia gas pressures. The system also uses a small gas trim flow upstream of the cascade nozzle to achieve the correct solids flow rate for a given gasifier chamber pressure. The advantage of this continuous high pressure solids discharge system is that it doesn't require the use of lock hoppers, will not plug, is very compact and fairly cheap. After 1.5 hours of high pressure solids flow, no measurable erosion of the piping and nozzle orifices were observed.

5.0 GASIFIER PERFORMANCE AT 5%RSD NON-UNIFORMITY

As noted above, the goal for injector flow splitter non-uniformity of less than 2 %RSD was not met for the larger sized injectors tested on this program. An analytical assessment was made to determine the reduction in gasifier performance (i.e., carbon conversion and cold gas efficiency) when using injector's having higher flow splitting non-uniformities. This analytical assessment was conducted using the baseline compact gasifier flow conditions for Illinois #6 bituminous coal, PRB sub-bituminous coal, Chalmette Petcoke, and Beulah-Zap North Dakota lignite as reported in Table 4.2.1 of the PWR compact gasifier specification by Sprouse (2004). These baseline gasifier performances were determined from a proprietary PWR 1-dimensional (1-D) kinetic code that was modified from an earlier gasification model by Sprouse (1980). This derived code was subsequently correlated against actual PWR experimental gasifier data from the 1970 and 80's. The slagging gasifier operating conditions found in Table 4.2.1 were selected on the basis of producing high cold gas efficiencies (above 82% higher heating value, HHV, basis) and essentially 100% carbon burnout.

The methodology followed below to evaluate the gasifier performance reduction effects on flow splitting non-uniformity is essentially a worse-case assessment. It assumes all injector orifices have the same coal flow rate except two -- one orifice running high with the other orifice running low. With this simplification, it can be shown that the increased coal flow rate through the high running orifice (on a non-dimensional or relative basis), $\Delta\dot{m}^*_{cs}$, is determined by:

$$\Delta\dot{m}^*_{cs} = S\sqrt{\frac{n-1}{2}} \tag{3}$$

where the variable S is again the relative standard deviation of the injector's flow splitting non-uniformity, and n is the number of coal orifices in the injector. This increased coal (or carbonaceous solid) flow rate was then added to the nominal flow rates used in the development of Table 4.2.1 of the Sprouse (2004) specification to increase the gasifier's input equivalence ratio for the 1-D kinetic model runs. These computer runs were made on the four carbonaceous solids identified above with $\Delta\dot{m}^*_{cs}$ calculated using various standard deviations, S, and orifices, n. These computer runs produced reduced carbon conversions, $\eta_{c,r}$, between 90 and 98% for the high flowing injector element which were reasonably curve-fit by the following linear equation:

$$\eta_{c,r} = \eta^{\circ}_{c}\left(1 - c_1\sqrt{2}\ \Delta\dot{m}^*_{cs}\right) \tag{4}$$

where the variable η_c° is the original gasifier carbon conversion under uniform flow splitting (S = 0) conditions [Table 4.2.1 in the Sprouse (2004) specification] and the constant c_1 is the curve-fit constant (c_1 = 0.22).

If the assumption is made that there is no downstream inter-element mixing (a worse case assumption), then one can show from continuity that the relative reduction in overall carbon conversion efficiency, $\Delta\eta_c^*$, due to a multi-element injector with non-uniform flow splitting is approximately:

$$\Delta\eta_c^* = c_1 \frac{S\sqrt{n-1}}{n} \tag{5}$$

Depending upon the number of elements, n, within the injector; Equation 5 shows that the relative reduction in carbon conversion, $\Delta\eta_c^*$, is very small for injector's operating at Bingham stress numbers above 4.0 where the flow splitting non-uniformity, S, is below 5 %RSD. For a six element injector, Equation 5 shows that the relative reduction in carbon conversion, $\Delta\eta_c^*$, will be below 0.4% -- while an eighteen element injector's reduction will be less than 0.25%.

In terms of the relative reduction in overall cold gas efficiency, $\Delta\eta_{cg,hhv}^*$, for a non-uniform splitting multi-element injector, one can also show a relatively simple relationship where use is made of the fact that the molar higher-heating-value (hhv) of gaseous hydrogen, H_2, is nearly identical to the heating value of carbon monoxide, CO, at 68.0 kcal/mol. This stoichiometric analysis shows the overall relative reduction in cold gas efficiency (on a higher heating value basis), $\Delta\eta_{cg,hhv}^*$, to be directly proportional to the overall relative reduction in carbon conversion, $\Delta\eta_c^*$, according to:

$$\Delta\eta_{cg,hhv}^* = \frac{1}{\left(1 - \dfrac{\dot{m}_{ox}\, Y_{O2}\, \hat{M}_c}{\dot{m}_{cs}\, \hat{M}_{O2}\, Y_c\, \eta_c^\circ}\right)} \Delta\eta_c^* \tag{6}$$

where the variable $\dot{m}_{ox}$ is the mass flow rate of the gaseous oxidizer reactant delivered to the gasifier, the variable $\dot{m}_{cs}$ is the mass flow rate of the carbonaceous solid reactant delivered to the gasifier, the variable Y_{O2} is the mass fraction of oxygen (O_2) within the oxidizer reactant, the variable Y_c is the mass fraction of carbon within the carbonaceous solid reactant, the constant $\hat{M}_{O2}$ is the molecular weight of oxygen (32.0 g/mol), the constant $\hat{M}_c$ is the

atomic weight of carbon (12.0 g/mol), and the variable η_c° is the gasifier carbon conversion under uniform flow splitting (S = 0) conditions as before. Using the reactant flow rates and mass fractions from Table 4.2.1 in the Sprouse (2004) specification, Equation 6 shows that the overall relative reduction in gasifier cold gas efficiency, $\Delta\eta^{*}_{cg,hhv}$, is just about double the relative reduction in overall carbon conversion for the four carbonaceous solids evaluated in Table 4.2.1. This means that the relative loss in cold gas efficiency using a multi-element injector with a flow splitting non-uniformity of 5 %RSD is essentially less than 0.8% for a six element injector and less than 0.5% for an eighteen element injector. Further details regarding the above cold gas efficiency stoichiometric analysis can be found in Appendix A of this report.

From the above analysis, one can see the relative insensitivity of slagging gasifier performance on flow splitting non-uniformity, S, in the 5 %RSD range. Hence, it was perhaps too stringent to set the program's flow splitting non-uniformity goal at the same level (i.e., 2 %RSD) that was experimentally obtained with the smaller splitters of Combs (1982) and Falk (1982).

CONCLUSIONS

Although the programmatic goal for flow non-uniformities of 2 %RSD (or less) was not achieved with the tested multi-element injectors, this program achieved a number of major milestones. These included: (1) the activation of a near commercial size ultra-dense phase solids flow test facility that can be operated plug free, (2) the successful scale-up of the PWR ultra-dense phase feed system from small tubing to piping at 400-tons/day using the model correlations developed from the 1980's, (3) the successful integration of capacitance style in-line velocity sensors to determine multi-element injector splitting performance, and (4) a non-dimensional Bingham stress analysis for the design of future high performance multi-element injectors over a wide range of sizes. Additional batch mode testing should be resumed at solids flow rates to 1200-tons/day to demonstrate the viability of the PWR feed system and multi-element injector design methodologies at the commercial scale. Finally, the EERC facility is ready for upgrade to continuous operation at 1,000 psia gasification simulation pressures by the addition of a recycle gas compressor and solids pump. Continuous operation will ultimately provide necessary life cycle-data on critical ultra-dense phase feed system components -- including the multi-element injector and high pressure dry solids pump -- prior to subsequent use in a commercial size gasification plant.

Currently, the injector's flow splitting non-uniforminty requirement for a compact PWR entrained flow gasifier has not been adequately determined. It is well known in the rocket engine industry that significant inter-element mixing due to the high energy release rates near the injector's face tends to smooth out initial

flow split non-uniformities. PWR multi-element gasifier testing from the 1970's indicates that injector flow splitting non-uniformities can be higher than 2 %RSD while still achieving good performance. A computer code similar to the National Aeronautics and Space Administration's (NASA's) standard methodology for flow splitting and mixing non-uniformity performance propagation -- Schuman and Beshore (1978) -- is being developed to further assess the flow splitting non-uniformity requirement. This code will incorporate the modified computer algorithms of Sprouse (1980) for coal combustion, gasification and liquefaction that was used in the simplified Section 5.0 analysis above.

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ACRONYMS AND ABBREVIATIONS

AFRPL	Air Force Rocket Propulsion Laboratory
CA	California
DOE	Department of Energy
EERC	Energy and Environmental Research Center
FE	Flow Element
FOD	Foreign Object Debris
FT	Flow Transmitter
GN2	Gaseous Nitrogen, N_2
HHV	Higher Heating Value
HPDT	High Pressure Discharge Tank
MN	Minnesota
NASA	National Aeronautics and Space Administration
NETL	National Energy Technology Laboratory
NTIS	National Technical Information Service
PRB	Powder River Basin
RSD	Relative Standard Deviation
PWR	Pratt & Whitney Rocketdyne
SDER	Standardized Distributed Energy Release
UND	University of North Dakota
U.S.	United States of America

APPENDIX A

COLD GAS EFFICIENCY STOICHIOMETRIC ANALYSIS

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A gasifier's cold gas efficiency (on a higher heating valve basis), $\eta_{cg,hhv}$, can be directly determined from stoichiometry considerations alone whenever methane or C2 (and higher) hydrocarbons and tars are not produced. This is usually the case for gasifiers operating at slagging conditions above 2500 F. By writing the chemical formula for the moisture-ash-free (maf) coal that was gasified as $CH_aO_bN_cS_dCl_e$ (where a, b, c, d, and e are the atomic element coefficients of a hypothetical coal molecule), the coal gasification reaction can be written as:

$$CH_aO_bN_cS_dCl_e(s) + f\,O_2(g) + g\,H_2O(g) \rightarrow$$

$$h\,CO(g) + i\,H_2(g) + j\,H_2O(g) + k\,CO_2(g) + c\,NH_3(g) + d\,H_2S(g) + e\,HCl(g)$$

where f, g, h, i, j, and k are reactant/product stoichiometric coefficients of the reaction.

From the above gasification chemical reaction, an elemental atomic carbon balance will show that:

$$h + k = 1 \tag{A1}$$

An elemental atomic hydrogen balance on the above reaction will further show:

$$2i + 2j + 3c + 2d + e = a + 2g \tag{A2}$$

And finally, an elemental atomic oxygen balance on this reaction yields:

$$h + j + 2k = b + 2f + g \tag{A3}$$

One can combine Equations A1 through A3 to show that:

$$\left(h + i \right) = \left[2 + \frac{1}{2} a - b - \frac{3}{2} c - d - \frac{1}{2} e \right] - 2 f \qquad \text{(A4)}$$

Now the molar higher heat of combustion for hydrogen gas, $\Delta H_{comb,H2,hhv}$, is well known and reported in the literature to be 68.32 kcal/mol. This value is almost identical to the heat of combustion for carbon monoxide gas, $\Delta H_{comb,CO}$, at 67.64 kcal/mol. Hence, the cold gas efficiency (expressed on a higher heating value basis), $\eta_{cg,hhv}$, can be readily defined for the gasified coal as:

$$\eta_{cg,hhv} = \left(h + i \right) \frac{\Delta H_{comb,H2,hhv}}{\Delta H_{comb,CHONS,hhv}} \qquad \text{(A5)}$$

where the variable $\Delta H_{comb,CHONS,hhv}$ denotes the molar higher heat of combustion of the moisture ash free coal for the gasified coal's hypothetical $CH_aO_bN_cS_dCl_e$ molecular formula.

Combining Equations A4 and A5 will show that the cold gas efficiency (hhv basis) is a function of only the input oxygen-to-gasified coal ratio, f, delivered to the gasifier according to:

$$\eta_{cg,hhv} = \frac{\Delta H_{comb,H2,hhv}}{\Delta H_{comb,CHONS,hhv}} \left\{ \left[2 + \frac{1}{2} a - b - \frac{3}{2} c - d - \frac{1}{2} e \right] - 2 f \right\} \qquad \text{(A6)}$$

It is interesting to see that the amount of steam reactant delivered to the gasifier, g, does not enter into the cold gas efficiency result.

Equation A6 shows that by lowering the oxygen gas to gasified coal ratio, f, one can directly increase the gasifier's cold gas efficiency. However, one can not continue lowering the oxygen-to-gasified coal ratio, f, to zero just to get the maximum cold gas efficiency, $\eta_{cg,hhv}$. This is because, at some point, low values of f lead to low gasifier temperatures where significant amounts of methane and C2 (or higher) hydrocarbon products are produced due to the low adiabatic gasifier temperature. In addition, low values of f also lead to soot (graphite) in the gasification product.

To ensure that a gasifier does not produce detrimental soot or applicable amounts of methane and C2+ hydrocarbons, a chemical equilibrium analysis or gasifier kinetic analysis should be performed. Some background into these types

of analyses can be found in the following American Institute of Chemical Engineers' manuscript: K.M. Sprouse, "Modeling Pulverized Coal Conversion in Entrained Flows," *AIChE Journal*, *26* (No. 6), 964 (1980).