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Dry Coal Feed System and Multi-Element Injector Test Plan

TOPICAL 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 multi-element injector. This report describes the layout, test procedures, instrumentation and data acquisition requirements for an ultra-dense phase multi-element injector and feed system to be operated at the University of North Dakota Energy and Environmental Research Center (UNDEERC).

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EXECUTIVE SUMMARY

This document describes the technical work related to the ultra-dense phase multi-element injector and feed system test planning activities at the University of North Dakota's Energy and Environmental Research Center (UNDEERC). This test plan covers the UNDEERC integrated test facility which contains (a) the primary high pressure feed system from the high pressure discharge tank through the multi-element injector assembly, and (b) the facility's secondary high pressure let-down system (including cyclone separator, baghouse, and atmospheric pressure coal storage silo) for returning the pulverized coal back to ambient pressure conditions within the facilities storage silo.

Under the current DOE cooperative agreement, the feed system will be tested under short duration (4 minute) batch mode conditions. However, provisions are also included within the test plan to leave the facility in a stand-by condition at the conclusion of the initial batch mode test for subsequent long duration dry coal pump testing in a continuous flow loop.

Two multi-element injectors will be tested under this program plan: a single tier 1-to-6 split injector, and a dual tier 1-to-18 split injector. The single tier 1-to-6 split injector will be tested at full flow conditions while the dual tier 1-to-18 split injector will be tested at 33% full flow conditions in order to demonstrate reasonable turn-down capability. Testing will be conducted under cold flow conditions to injector discharge pressures of 1,000 psia.

Both injectors are designed to maintain flow non-uniformities among all the elements below 2% RSD (relative standard deviation). This is consistent with earlier testing at PWR in the 1970's which demonstrated measured flow non-uniformities among the elements below 1.2% RSD – Combs (1982) and Falk (1982).

Two different coal feedstocks will also be tested. An Illinois #6 bituminous coal dried to approximately 2 wt% moisture and a Powder River Basin (WY) sub-bituminous coal dried to approximately 15 wt% moisture. Both coals will be pulverized to standard industrial grind (nominally 70 wt% passing through 200 mesh screen). At 2 and 15 wt% moisture contents these coals should have reasonably different coefficients of cohesion for understanding the robustness of the ultra-dense phase feed system and injector splitters.

EXPERIMENTAL METHODS

1.0 INTRODUCTION

The commercial development of low-cost coal gasifiers (small and efficient with high on-stream availability) requires the development of high pressure, ultra-dense phase, dry-coal feed systems and multi-element injectors. Pratt & Whitney Rocketdyne (PWR – a United Technologies Company) started the development work on these feed system in the 1970's – see, e.g., Oberg and Hood (1980) and Sprouse and Schuman (1983). These pulverized coal feed systems were successfully demonstrated on a number of U.S. Department of Energy (DOE) and company funded test programs to pressures of 1,500 psia and coal flow rates of approximately 50 tons/day. Uniform multi-element coal injectors were also incorporated into these feed systems and successfully tested with up to 6 injection elements (using proprietary splitter designs). This work was terminated in 1985 with the collapse of world oil and gas prices.

With the return of high oil and gas prices in 2002, PWR re-started its design activities on high pressure (1,000 psia) commercial scale dry pulverized coal gasifiers in the 1,200 to 3,000 tons/day range. These commercial scale design efforts show the need of developing rapid-mix multi-element injectors whereby each element flows approximately 3.5 tons/hr of standard industrial grind pulverized coal (i.e., 70 wt% passing through 200 mesh, 74-μm opening, screen). This requires new injector designs for these coal feed systems that incorporate flow splitters achieving between 18 and 36 coal injection elements.

In 2005, PWR secured funding in a cooperative effort with the U.S. Department of Energy (Contract No. DE-FC26-04NT42237) to build a PWR ultra-dense phase coal feed system at the near commercial scale level of 400 tons/day. This feed system is to be a scaled up version from previous high pressure (1,000 psia) PWR systems tested in the 1970's and 80's at coal flow rates approaching 50 tons/day (an 8-to-1 scale-up). However, the feed system is to incorporate full-scale size injector elements capable of handling 3.5 tons/hr per element in either a 6-element injector configuration or an 18-element configuration. The feed system must also accommodate alternate types of dry pulverized solid coal pumps as pumping technology is expected to advance beyond current state-of-the-art cycling lock hoppers.

The University of North Dakota's Energy & Environmental Research Center (EERC) in Grand Forks, ND was awarded a sub-contract by PWR in 2005 to design, build and operate the test facility for demonstrating this high-pressure, ultra-dense phase feed system and multi-element coal injector at near-commercial scale flow rates. It is expected that all testing will be conducted at coal flow rates near 400 tons/day -- with the possibility of a few short duration

(20-second) runs at 1,200 tons/day, if time and funding allow. Although this plan only covers blow-down performance operation using a series of nominal 4-minute tests, additional long duration testing will be conducted with a novel solids pump after completion of this program.

The feed systems' atmospheric storage silo, high pressure discharge tank, multi-element injector, injector chamber, cascade nozzle, low-pressure silo/tank transfer line, high pressure tank/injector feed line, and high pressure chamber/nozzle transfer line were designed and fabricated by PWR. The facility's baghouse, cyclone, structural steel tower, interconnecting gas piping, and control system were designed and fabricated by EERC.

2.0 TEST OBJECTIVES

The primary objectives under this test plan are to: (1) demonstrate plug free operation of a 400 tons/day ultra-dense phase feed system at 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%.

To this end, the PWR feed system/injector assembly shown in Figure 1 will be operated in the batch mode flow configuration. For EERC testing, the overall flow diagram will also include a pressure letdown system containing a cyclone gas/particle separator and baghouse as shown in Figure 1a. Here, pulverized coal will be manually loaded into the 1,000-gal atmospheric pressure storage silo. This silo will charge the 700-gal high pressure discharge tank through a series of manually and remotely operated ball valves located within a 15-ft vertical transfer piping section. Once the high pressure discharge tank is loaded with coal and pressurized by nitrogen gas (GN2) to operating conditions, its lower ball valve will be opened allowing pulverized coal to flow at ultra-dense phase conditions through a length of feed system piping and on through the multi-element injector. The PWR feed system/injector assembly also contains a GN2 gas pressurization line to the high pressure discharge tank for controlling the coal flow rate to the multi-element injector. Higher gas pressures result in higher coal flow rates while lower pressures produce lower flow rates.

As part of a follow-on program or future privately funded activity, the vertical transfer piping section can be removed and replaced by an advanced high-pressure solids pump for continuous feed system operation. Dry coal pumps appear to offer significant advantages in terms of cost and efficiency in relationship to state-of-the-art cycling lock hoppers.

There are scheduled to be at least twelve 4-minute blow-down tests with this hardware in the current project using two different ranks of coal (six tests per each rank). It is expected that the two coal ranks will be: an Illinois #6 bituminous coal dried to about 2 wt% moisture, and a low rank coal such as Powder River Basin (PRB) sub-bituminous or North Dakota lignite dried to approximately 15 wt% moisture. Montana or North Dakota lignite may be substituted for the PRB coal. Both coals will be supplied to EERC already pulverized to a standard industrial grind of 70 wt% through 200 mesh screen.

The expected test conditions for these twelve experiments are shown in Table 1 below. At full-flow conditions, the feed system is designed to operate at low coal velocities due to long life erosion considerations. At 1-to-3 turndown conditions, the feed system coal velocities will be slower by approximately 1/3. In all cases, the coal feed system operates at very low void fractions, ε (approximately 55%), and associated carrier gas flow rates.

If after completion of this test matrix additional time and funding remain, a series of short 20-second tests with the 1x18 injector at full-flow coal feed conditions (i.e., a 27.8 lbm/sec coal flow rate and 30 ft/sec line velocity) may be attempted. Early indications are that the EERC 400 tons/day rated facility is capable of handling 1,200 tons/day on a relatively short flow time basis of 20-seconds. For these possible tests, the nominal feed system pressure will be substantially reduced to approximately 300 psia from the 700 to 1050 psia range shown in Table 1.

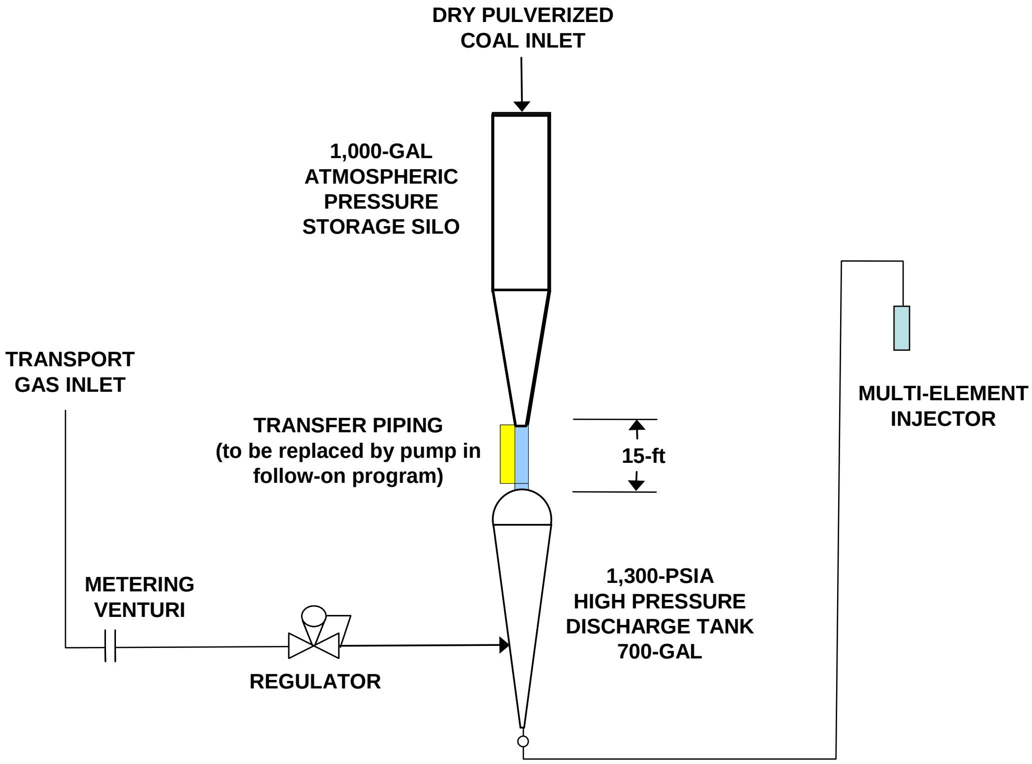

Figure 1. 400-Ton/Day Ultra-Dense Phase Feed System and Multi-Element Injector

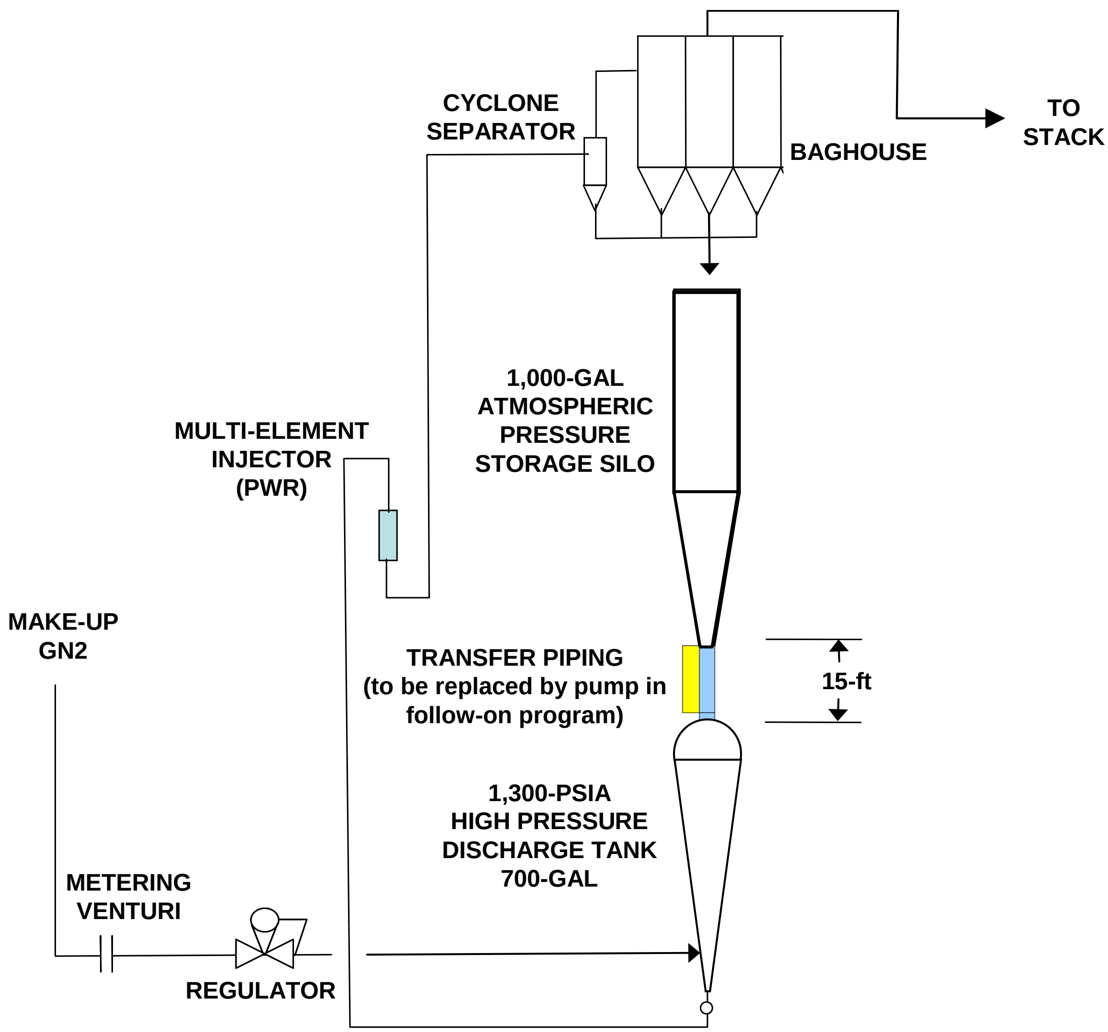

Figure 1a. 400-Ton/Day Ultra-Dense Phase Feed System Flow Diagram at EERC (Batch Mode)

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

3.0 FEED SYSTEM HARDWARE DESCRIPTION

This section describes the PWR supplied test equipment for conducting the experiments listed in Table 1 of this plan.

3.1 Multi-Element Injectors

Two multi-element injectors will be tested on this project as shown in Table 1. The first will be a 1x6 multi-element injector and the second will be a 1x18 multi-element injector. Both injectors will use the same common mounting blind flange containing eighteen equally spaced 3/4" tube ports in two circular rows for splitter connections. At the facility's rated 400 tons/day coal flow rate, the 1x6 multi-element injector will run at its design full-flow condition while the 1x18 injector will run at its 1/3-flow condition.

Each injector will be instrumented with six electrical time-of-flight velocity sensors – Thermo Electron Corporation (2006) on the injector's individual elements for measuring flow splitting uniformity. The flow splitting non-uniformity of each injector will be measured by the relative standard deviation (RSD), s, of velocity as defined by:

$$s = \sqrt{\frac{1}{(n-1)} \sum_{i=1}^{n} \left(\frac{v_i}{\hat{v}} - 1 \right)^2} \tag{1}$$

where the variable n is the number of injection elements whose velocities were measured (i.e., 6), the variable v_i denotes the measured coal velocity (ft/sec) of the ith injection element, and the variable $\hat{v}$ is the average measured coal velocity among the injector's elements according to:

$$\hat{v} = \frac{1}{n} \sum_{i=1}^{n} v_i \tag{2}$$

The measure of success for each tested injector will be that their internal flow passages do not plug with coal and that their non-uniformity, s, is less than 2 %RSD. For PWR injectors operating within ultra-dense phase feed systems (void fractions, ε, below 60%), velocity non-uniformity is a good measure of the flow splitting uniformity since all coal particles are locked in physical contact with one another to prevent coal separation or stratification within the flow field. This would not be the case for an injector operating at void fractions, ε, over 70%. In this case, an additional solids density meter (in series with each velocity meter) would be required.

When testing the 1x18 injector, only 1/3 of the injection elements will be instrumented with velocity meters. Should one of the non-instrumented elements become plugged, detection may become difficult. Hence, periodic inspections of the injector face plate with a PWR supplied boroscope will be conducted at the conclusion of some of these 1x18 injector test.

3.1.1 The 1x18 Multi-Element Injector.

The main injector to be tested on this project will be the 1x18 injector shown in Figure 2 below. This injector employs two tier splitting which has never been performed by PWR. The first tier split is performed a 1x3 splitter and the second tier split is performed by three 1x6 splitters. The inlet to the injector is a standard American National Standards Institute (ANSI) 1,500-lb 2-1/2"Sch.160 pipe flange that feeds the first tier splitter.

Located below the second tier splitters are the six electronic solids velocity meters mentioned above – two meters for each of the three 1x6 second tier splitters. The outlets of each meter together with the 12 non-metered elements are connected to the injector chamber's forward closeout flange. This closeout flange bolts onto the conical injector chamber (Figure 3). The conical injector chamber's outlet is an ANSI 1,500-lb 1-1/4"Sch.XX pipe discharge flange assembly which mates to the injector's 1-1/4"Sch.XX dump line.

The conical injector chamber's forward flange contains four bypass nozzles and one static pressure tap port. The four bypass nozzles are connected to 1/2" (0.049" wall) tubing and the static pressure tap port is connected to 1/4" (0.028" wall) tubing. As seen in Table 1, the bypass nozzles continually flow GN2 gas throughout the duration of the tests and increase the void fraction of the discharge stream before it enters the dump line.

The injector chamber's forward closeout flange (which holds the 18 elements) is shown in Figure 4. The 18 element holes in this flange are drilled and tapped for passing the injector's tubing completely through the flange and holding the tubing in place with standard Swagelok fittings. In addition to these holes, this flange also contains a discharge pipe for connection to a burst disk diaphragm. This pipe is designed to minimize the chance of plugging during a ruptured disk venting condition. The maximum design pressure rating for the 1x18 multi-element injector and the conical injector chamber is 1,430 psia. This pressure rating shall be ASME Boiler and Pressure

Vessel Code (BPVC) stamped onto the side of the conical injector chamber. It is required that the burst disk diaphragm's rupture condition will be below this maximum design pressure rating.

It should be noted that the 1x18 multi-element injector will be the second injector tested. The first injector to be tested at EERC will be the 1x6 injector (described below) and it will be initially shipped to EERC for direct mounting into the facility. The 1x18 multi-element injector will be delivered to EERC in a quasi-disassembled fashion. Only the 2-tier splitter assembly will be in completed form. At the conclusion of 1x6 multi-element injector testing, EERC will be required to remove the 1x6 injector piping elements from above the injector chamber's forward closeout flange and install the 2-tier splitter assembly along with its remaining lower tubing together with the six velocity meters. The mass of the forward closeout flange and splitter tubing assembly is approximately 1.5-ton. The lower conical injector chamber mass is approximately another 1.5-ton.

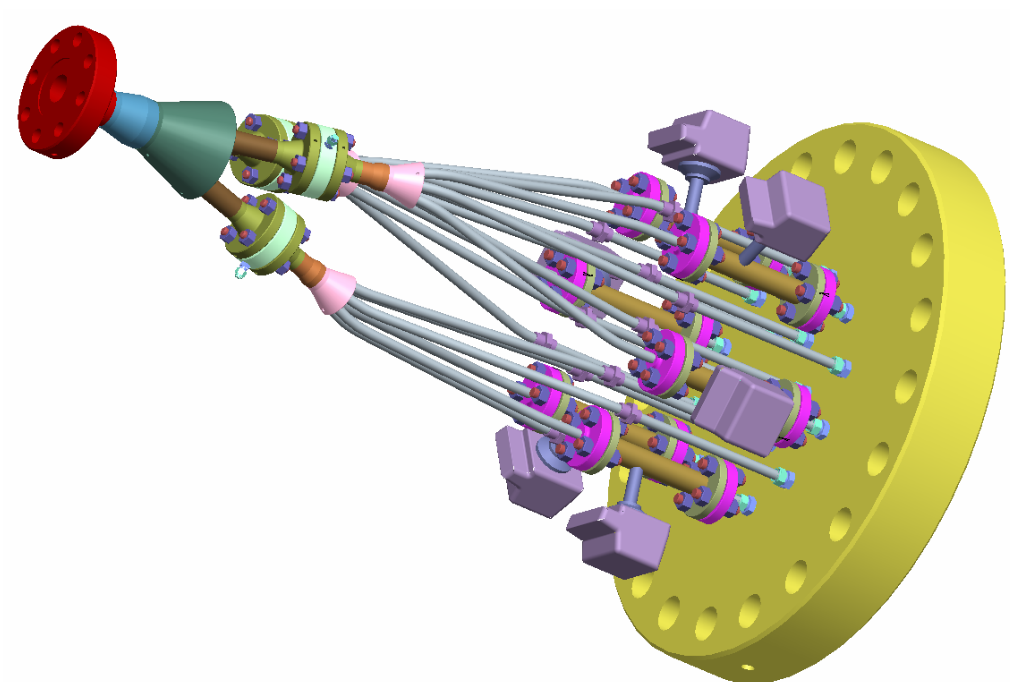

Figure 2. The 1x18 Two Tier Multi-Element Injector (Drawing 7R110700A1)

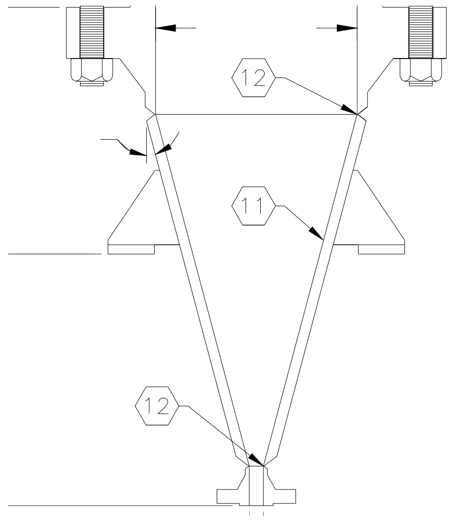

Figure 3. Conical Injector Chamber (Drawing 7RE6392)

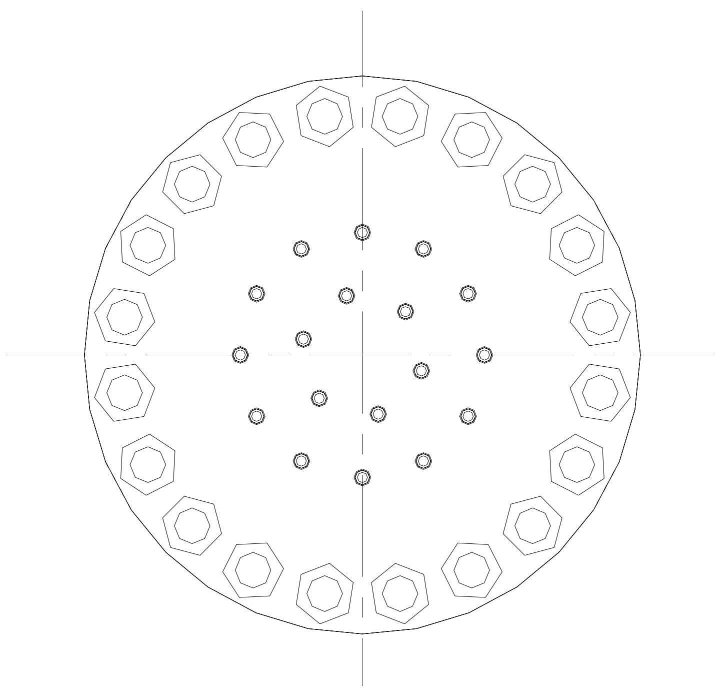

Figure 4. Injector Chamber Forward Closeout Flange (Drawing 7R110740)

3.1.2 The 1x6 Multi-Element Injector.

The first injector to be tested on this project will be the 1x6 multi-element injector shown in Figure 5. This injector employs single tier splitting similar to that used in PWR testing from the 1970's (which was performed at much lower coal flow rates of only 50 tons/day and associated smaller element sizes). The inlet to this injector is a standard ANSI 1,500-lb 1-1/4"Sch.80 pipe flange that feeds the single tier splitter. Between the single tier splitter and injector chamber closeout flange are the six solids velocity meters used to monitor the flow split uniformity.

The complete 1x6 multi-element injector assembly (including the conical injector chamber and discharge assemblies described above) will be assembled at PWR and shipped to EERC as a complete assembly. Its total ship weight is expected to be 3-tons. After tests on the 1x6 multi-element injector are complete, EERC will remove the injector's 1-1/4"Sch.80 inlet flange and splitter from the injector body's closeout flange and rebuild the upper injector assembly into the 1x18 multi-element configuration described in the previous section from the 2-1/2"Sch.160 inlet flange and two-tier splitter parts supplied separately by PWR. The maximum design pressure rating for this 1x6 multi-element injector assembly will also be set at 1,430 psia (same as the 1x18 multi-element assembly).

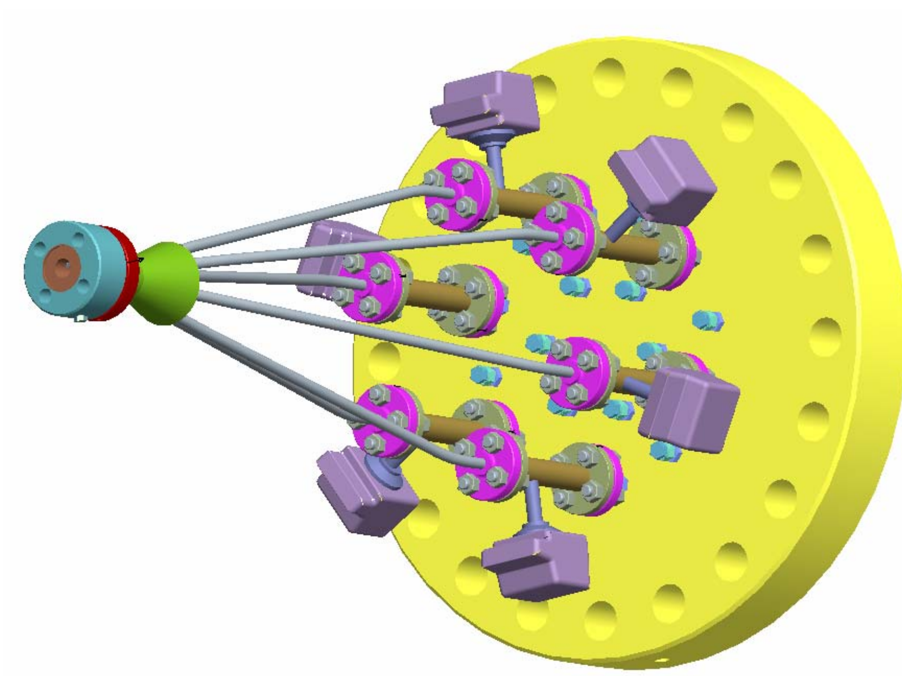

Figure 5. The 1x6 Multi-Element Injector (Drawing 7R110701A1)

3.2 Pressurization Hopper/Tank Assembly and Feed Line

Two tanks will be supplied to the facility by PWR and used within the PWR ultra-dense phase feed system for increasing the pulverized coal's static gas pressure from atmospheric conditions to run conditions approaching 1,300 psia. This hopper/tank assembly is shown in Figure 6 along with the main 15-ft interconnect drop-down pipe sub-assembly. At the top of the assembly is a 1,000-gal atmospheric silo shown with additional detail in Figure 7.

Attached to the bottom of the storage silo is the drop-down pipe sub-assembly shown in Figure 8. This drop-down pipe sub-assembly contains a silo cone reducer spool, a low pressure purge ring, a low pressure ball valve, a vent spool, a bellows spool, a low pressure purge ring, a high pressure ball valve, and a high pressure expansion spool. PWR will also be supplying the ball valve actuator for this assembly which is expected to be pneumatically actuated. The high pressure ball valve will use a hand operated wheel. The total 15-ft length of this interconnect drop-down pipe sub-assembly was designed so that this sub-assembly could be removed and replaced by a continuous operating 400 tons/day dry pulverized coal pump on a subsequent program. The maximum design pressure rating at the bottom of the atmospheric silo (Figure 7) and the drop down pipe sub-assembly (above the high pressure ball valve) will be 19 psia (or 4 psig) which is the amount of gaseous pressure head developed by the silo's coal bed height at the ball valve GN2 purge ring.

Connected to the bottom of this drop-down pipe sub-assembly is a 700-gal high pressure discharge tank shown with additional detail in Figure 9. The top of this tank contains a number of nozzles for gas venting, filling and pressurization. At the bottom of this tank is a discharge valve spool sub-assembly for feeding the pulverized coal into a 2-1/2"Sch.160 feed pipe – see Figure 10. This discharge valve spool sub-assembly contains two purge rings and two pneumatically actuated ball valves. The lower ball valve is required for facility safety to prevent uncontrolled high pressure discharge tank venting should the upper primary ball valve fail to close before the discharge tank is emptied of all pulverized coal. Such high pressure uncontrolled venting of the discharge tank would probably damage both the atmospheric cyclone separator and baghouse to be described later in Figure 17. The maximum design pressure rating for the high pressure discharge tank is 1430 psia. This pressure rating will be ASME BPVC stamped on the side of the vessel and a burst disk diaphragm capable of rupturing at a pressure below this value must be installed.

Connecting the bottom of the high pressure discharge tank to the multi-element coal injector is the 2-1/2"Sch.160 feedline as shown in Figure 11. This feedline is designed to produce a low solids velocity at the design 400 tons/day solids flow rate.

The feed system piping is designed to minimize ultra-dense phase flow line plugging -- and if plugging should occur to provide relatively easy access and line disassembly for solids removal. The maximum pressure rating for both feedlines shall be taken at the full facility rated pressure of 2100 psia.

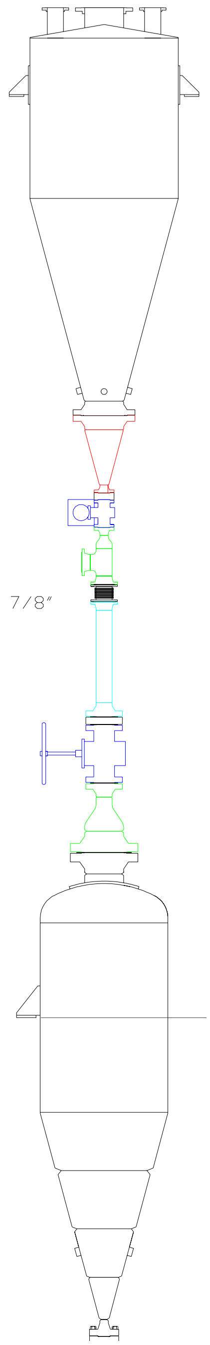

Figure 6. Pressurization Hopper/Tank Assembly (Drawing 7R109703)

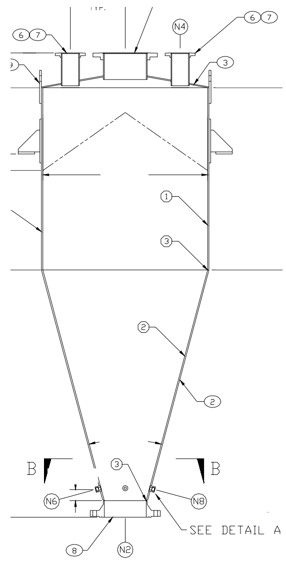

Figure 7. 1,000-gal Atmospheric Silo (Drawing 7R109632)

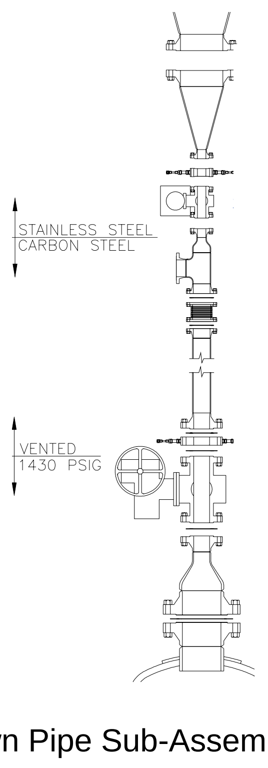

Figure 8. Drop Down Pipe Sub-Assembly (Drawing 7R109726)

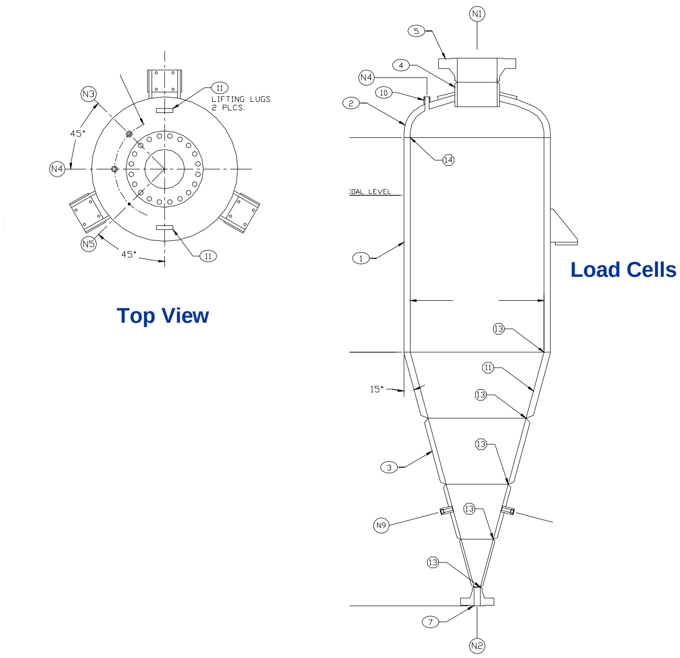

Figure 9. 700-gal High Pressure Discharge Tank (Drawing 7RE6393)

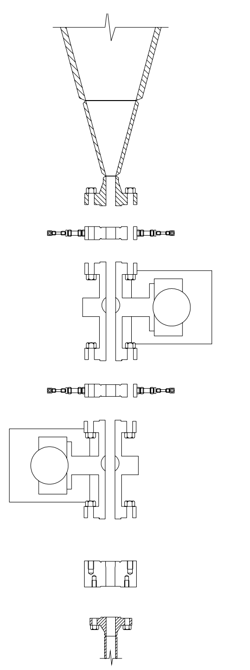

Figure 10. Discharge Tank Valve Spool Sub-Assembly (Drawings 7R109718)

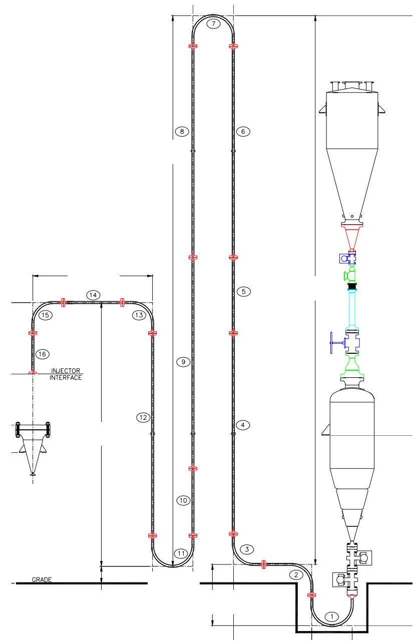

Figure 11. Primary 2-1/2"Sch.160 Feed Line (Drawing 7R109703)

3.3 Pressure Letdown System

The pressure letdown system is composed of a 1-1/4"Sch.XXS dump line (Figure 12) and a multi-orifice cascade pressure letdown nozzle (Figure 13). The 1-1/4"Sch.XX dump line connects the exit of the conical injector chamber to the inlet of the cascade nozzle. The purpose of the dump line is to provide enough pressure drop downstream of the injector chamber so that the flow void fraction is significantly high before entering the cascade nozzle. Due to the uncertainty in the pressure drop analysis for this section of piping (where the solids flow goes from ultra-dense phase to dilute phase flow, this length of piping section is capable of being re-assembled to a number of discrete intervals.

The multi-orifice cascade pressure letdown nozzle (Figure 13) is designed to expand the solids discharge flow from a high inlet void fraction (at static gas pressures of 200 to 300 psia) to an exit void fraction over 99 vol% (at a static pressure of about 17 psia). The cascade pressure letdown nozzle exits into a 6"Sch.40 pipe section for feeding EERC's particle cyclone separator. The cascade nozzle is designed to operate in a horizontal orientation. The maximum design pressure rating for both the dump line and cascade pressure letdown nozzle is 1430 psia.

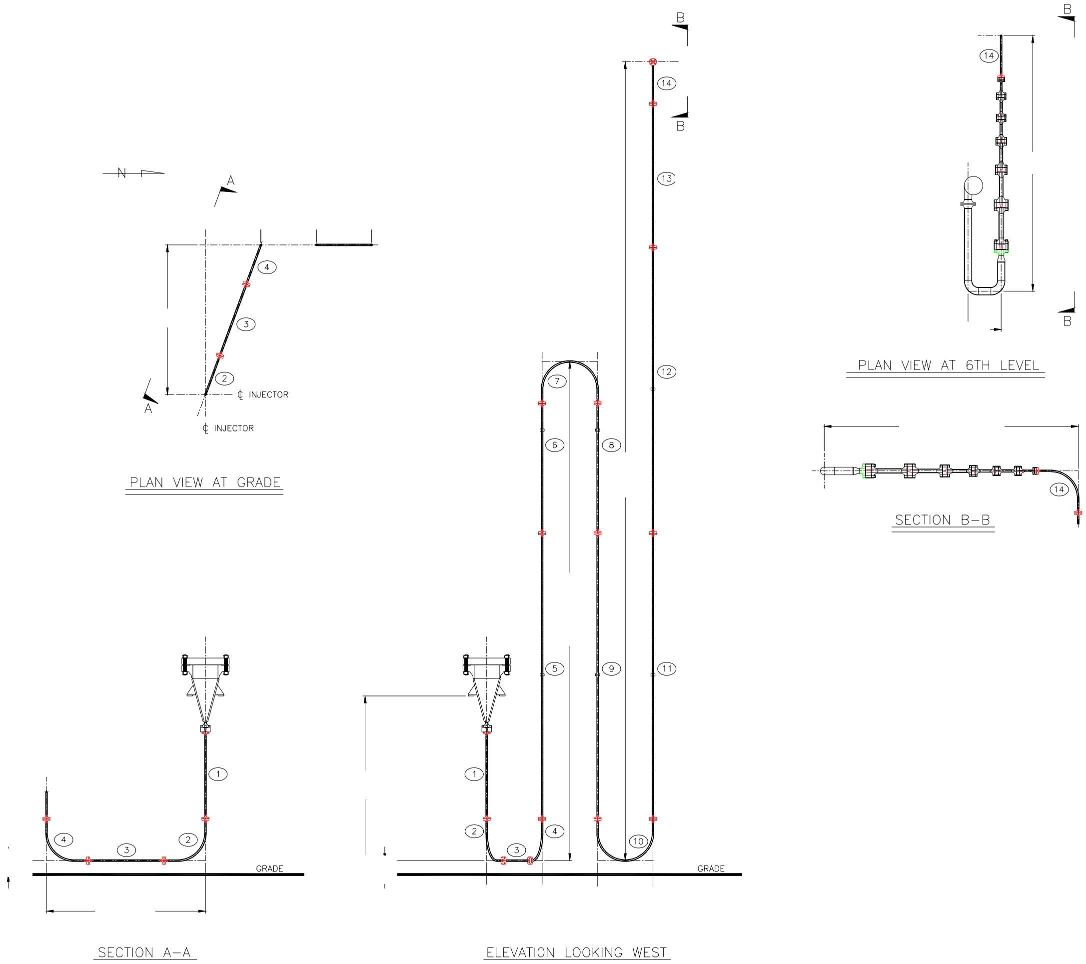

Figure 12. 1-1/4"Sch.XX Injector Discharge Dump Line (Drawings 7R109704, 705, & 706)

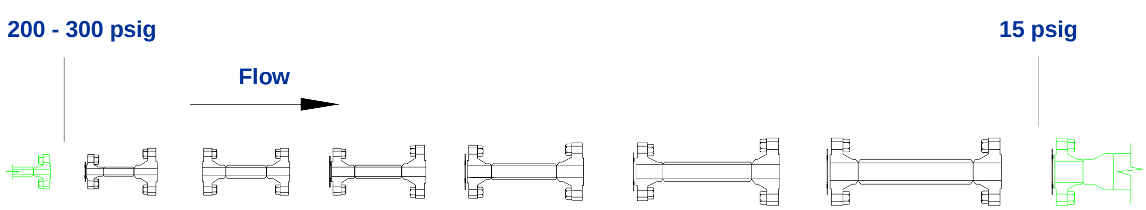

Figure 13. 7-Orifice Cascade Pressure Letdown Nozzle (Drawing 7R109740)

4.0 TEST FACILITY DESCRIPTION

All testing under this plan will be conducted inside the southeast high bay building (Building X) at the EERC facility on the University of North Dakota campus (Grand Forks, ND). This high bay facility is shown in Figure 14.

a) Outside View (looking north) b) Inside View (east wall)

Figure 14. Ultra Dense Phase Flow Test Facility at EERC

4.1 Physical Layout

The elevation and plot plans for the Ultra-Dense Phase Feed System Test Stand within the EERC High Bay Facility are shown in Figure 15 below. The test stand is located in southwest corner of the building shown in Figure 14. The high pressure discharge tank and conical injector chamber are hung from the stand’s 2nd level while the atmospheric storage silo and baghouse are located at the 5th level. The cyclone separator is mounted on the 6th level directly above the atmospheric storage silo together with the cascade pressure letdown nozzle. In order to make a 15-ft separation between the top of the discharge tank and the bottom of the storage silo for subsequent installation of a high pressure solids coal pump, a small pit will be dug into the facility’s floor to accommodate the high pressure discharge feed line’s U-bend. The test stands personnel staircase is located on the facility’s south wall.

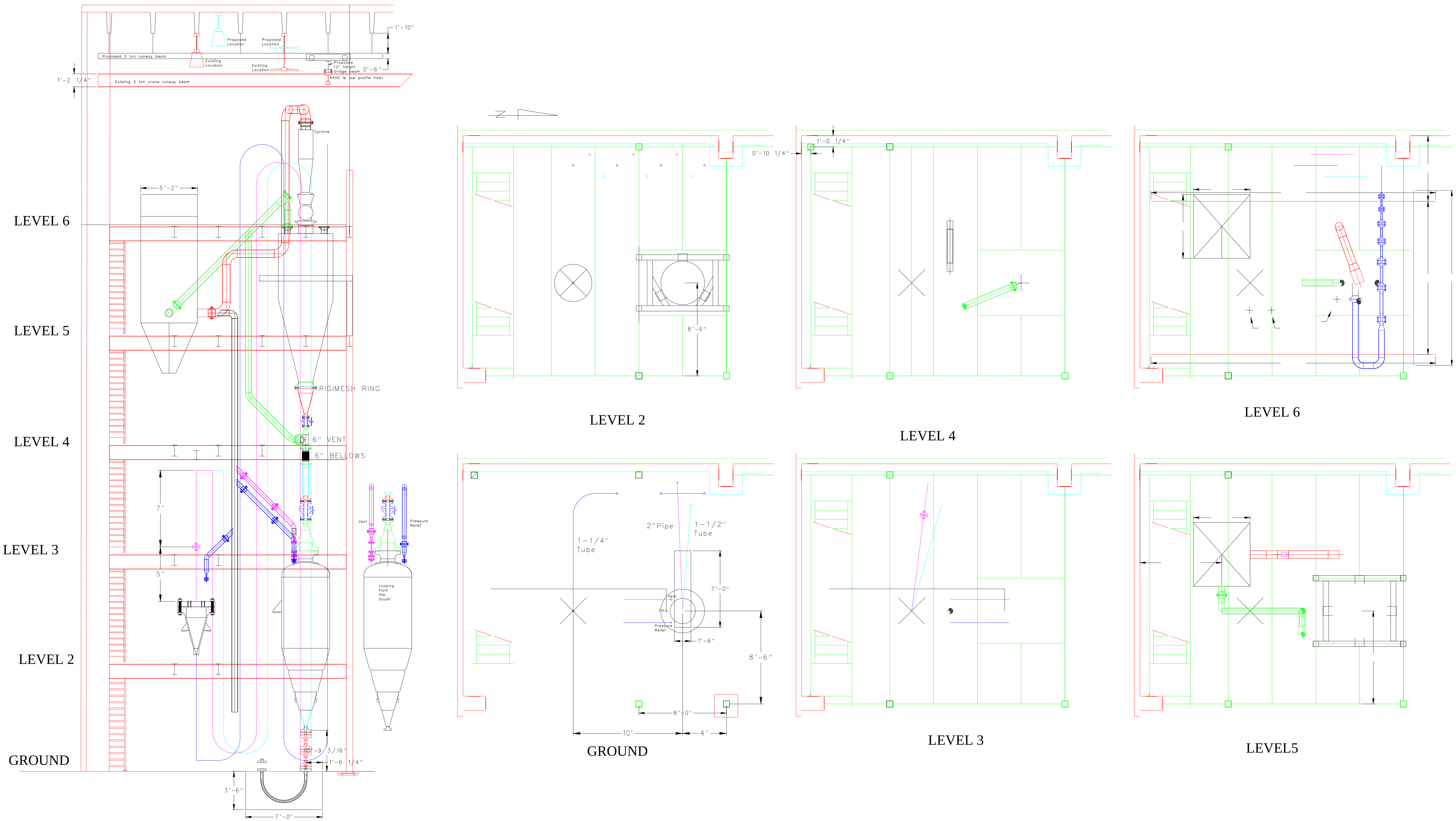

Figure 15. Test Stand Elevation and Plot Plans – Southwest Corner of Building (PWR Drawings 7R109700, 701 & 702 or UNDEERC Drawing 010406drh-version2000)

4.2 Piping and Instrumentation Drawing (P&ID)

The P&ID for the ultra-dense phase feed system test stand (not included) shows all the GN2 purge lines, vent lines, and flow meters in addition to the main process flow lines given in Figure 1a.

4.2.1 GN2 Purge and Pressurization Systems. GN2 purging is introduced into many areas of the coal's process flow lines to ensure smooth and reliable coal transport. All GN2 flow comes to the test stand initially at 2100 psia from the EERC facility's main LN2 pumping system. During a 4 minute blow down test, the expected GN2 supply pressure is expected to drop to about 1800 psia following the test's conclusion.

4.2.2 Vent and Depressurization Lines. The feed system contains a number of high pressure vent and depressurization lines on both the high pressure discharge tank and conical injector chamber assembly.

5.0 INSTRUMENTATION AND DATA RECORDING

The primary data to be observed and recorded during these tests are: (1) the injector's flow splitting uniformity from Equations 1 and 2 above together with the underlying solids velocity measurements (as described in Section 3.1), (2) the static gas pressure and differential gas pressure measurements as indicated on the P&ID, (3) the mass flow rate GN2 pressurization gas into the high pressure discharge tank, (4) the mass flow rate of GN2 gas exiting the baghouse, and (4) the mass flow rates of both the solid coal and GN2 transport carrier gas exiting the high pressure discharge tank. For all flow meters which use independent temperature, pressure, and load cell measurements to determine gas and solids flow rates, EERC will also be required to record and report this underlying data to PWR in addition to the meter's calculated flow rate.

Determination of the flow rates for the solid coal and GN2 transport carrier gas exiting the high pressure discharge tank are to be calculated from the tank's load cell measurements together with the pressurization gas mass flow rate, the tank's measured static gas pressure from transducer, and the tank's measured gas temperature. From these four underlying measurements; the coal flow rate, $\dot{m}_{coal}$, and the GN2 transport carrier gas flow rate, $\dot{m}_{g,tran}$, shall be calculated from the following two equations and recorded with the other data:

$$\dot{m}_{coal} = \frac{-\left(\frac{d\, W_{tank}}{d\, t}\right)}{\left(1 - \frac{\rho_g}{\rho_{coal}}\right)} \quad (3)$$

and:

$$\dot{m}_{g,tran} = \dot{m}_{g,pres} - \frac{\rho_g\, \dot{m}_{coal}}{\rho_{coal}} \quad (4)$$

where the variable W_{tank} is the instantaneous weight of the high pressure discharge tank assembly as measured by the tank's load cell (lbm), the variable t is the time (sec), the variable ρ_g is the density of the GN2 gas within the high pressure discharge tank as determined by independent static pressure and temperature measurements within the tank (lbm/ft^3), the variable ρ_{coal} is the true solids density of the coal (including moisture) at a void fraction of 0 vol% (typically somewhere around 90 lbm/ft^3), and the variable $\dot{m}_{g,pres}$ is the measured pressurization GN2 gas flow rate into the high pressure discharge tank (lbm/sec).

5.1 Transducers and Sensors

All instrumentation noted on the above P&ID as a transmitter will have their outputs recorded by EERC and given to PWR for review at the conclusion of each test. All of this instrumentation will be provided by EERC (with the exception of the six velocity transmitters to be supplied by PWR).

EERC will be responsible for maintaining each sensor's calibration uncertainty over the test program's duration. Periodic certifications of these calibration uncertainties will be provided by EERC to PWR on at least a bi-weekly basis. The certification procedures to be used by EERC to verify these sensor uncertainties are at the discretion of EERC and will be reported to PWR.

5.2 Data Recording

Run data from all transducers and sensors (except two facility pressure gauges) will be digitized and recorded by the facility computers for post-test retrieval, tabulation, and graph plotting. Sampling frequency will be at the nominal 1-Hz level. ASCII data files shall as a minimum be recorded onto CDs and delivered to PWR. ASCII data files may also be submitted as MS DOS ASCII data files via the PWR NEXPRIS system. Each record (or line) shall start with “time” in the first column and all transmitter and computed data in subsequent columns.

In addition to recording the time, temperature, pressure, velocity, and weight data, the facility computers shall also compute flow rate data for the baghouse discharge gas, coal, coal carrier gas, and coal splitting uniformity. These flow rates shall be calculated from standard American Society of Mechanical Engineers (ASME) protocols -- see, e.g., Perry and Chilton (1973) -- or the equations in this report.

6.0 TEST PROCEDURES

Test related activities will be conducted in accordance with established EERC procedures and generally accepted industry safety practices. At least 30 calendar days before the first pressurized coal blown-down test, Rocketdyne will submit a test request to EERC test operations for review and comments. After receiving any comments from EERC, the final test request will be submitted 24 hours prior to the first blow-down test date which should coincide with EERC’s “Test Readiness Review” (TRR) to be conducted at the EERC facility with PWR personnel present.

Each test request provided by Rocketdyne will specify the test conditions and hardware configuration for that test. Checkouts according to EERC facility operations procedure will be conducted prior to all tests for electro-mechanical systems, fluid systems, and instrumentation. An injector chamber leak check will be conducted after every injector configuration change. A safely completed blow-down test may be considered in lieu of additional leak check unless the injector and feed system assemblies have been in any way compromised. The injector and feed system assemblies are compromised whenever any pressure holding joint, seal, or fitting has been broken.

After the first 30 minutes of solids flow tests, the injector and feed system assemblies will be inspected for erosion. These assemblies can be visually inspected using facility borescopes, and physical measurements of the feed line walls. Any measurements showing excess erosions shall be reviewed by both EERC and PWR personnel. In many cases, larger erosions may be tolerated after subsequent ANSI piping code calculations are performed before piping replacement is required. These larger erosions will be reviewed on a case by case basis. Immediately following each test, EERC will provide PWR with detailed digital measurement data for preliminary data evaluation.

All test requests, submitted to EERC for approval, will contain a proposed control room check list for the EERC test engineer. Included on the check list will be the expected valve position-time schedule for (among others) the high pressure discharge tank's bottom valve along with critical "redline" automatic test cut-off and shut-down parameters. Prior to the transfer of any pulverized coal in the pilot-scale facility, it will be necessary to purge the system with nitrogen gas to reduce oxygen concentration to <6 vol% in order to eliminate the potential for a dust explosion.

7.0 TEST PROGRAM

The test program consists primarily of the twelve pressurized blow-down tests listed in Table 1 in addition to various system and valve actuation checkouts conducted prior to these twelve tests and described in further detail below. Following system and valve actuation checkouts, EERC will conduct a TRR with PWR personnel present prior to running the first pressurized blow down test.

7.1 SYSTEM AND VALVE ACTUATION CHECKOUTS

After the facility installation is complete, EERC will conduct a series of leak checks and valve actuation checks before any pulverized coal is loaded into the atmospheric storage silo. Leak checks are important since any leaking joints within the feed lines down stream of the high pressure discharge tank could subsequently lead to coal plugs by starving the transport lines of the minimal required carrier gas under ultra-dense phase flow conditions. Valve actuations under normal run start-up and shut-down conditions together with "redline cut" shutdown conditions need to be verified. Also, all GN2 purge flow rates through purge lines need to be verified against the facility supply pressure. The discharge venturi downstream of the baghouse will be used to provide this flow rate information.

Following completion of this initial checkout, a small amount of pulverized coal will be loaded into the atmospheric storage silo and the gravity free fall "hour glass" loading capability of the high pressure discharge tank will be investigated.

7.2 PRESSURIZED BLOW DOWN TESTING

At the conclusion of the system checkouts described in Section 7.1 above, EERC will load 700-gal of pulverized coal into the high pressure discharge tank and conduct the TRR with PWR engineers present prior to running test number 1 of the Table 1 test matrix. It should be noted that the flow rate and pressure drop conditions given in this table were developed from three sources. The pressure drops between the high pressure discharge tank and conical injector chamber were calculated from the Bingham fluid equations given by Sprouse and Schuman (1983 and 1986). The pressure drops in the dump line between the conical injector chamber and cascade nozzle were calculated from standard Fanning or Darcy pipe flow equations for isothermal compressible flow as given by Perry and Chilton (1973). Finally, the pressure drops across the seven orifice cascade nozzle were subsequently determined for two-phase (gas/solids) flow according to the recommended flow restriction equations of Fisher Controls (1977).

The test matrix of Table 1 starts at relatively low gas pressurization conditions within the high pressure discharge tank. Such conditions provide more margin against solids line plugging before moving to the higher injector chamber pressure of 1,000 psia.

8.0 PWR/EERC RESPONSIBILITIES

Test and post-test responsibilities between PWR and EERC fall into the following general categories. PWR is responsible for: (1) selecting the tests to be included within the Test Matrix, and (2) for completing all post-test analytical evaluations of the recorded test data. EERC is responsible for: (1) maintaining the test facility and its mechanical and instrumentation components in good repair and calibration over the program's duration, (2) leading and conducting all test operations within the facility (PWR personnel are only advisors to the assigned EERC test engineer), and (3) providing all recorded test data to PWR at the conclusion of each tests for analysis. No test will be conducted without PWR and EERC management approval of a "Test Request" document covering the particular proposed test to be preformed from the Test Matrix.

At the conclusion of the current test program, we expect to use the facility for additional dry coal flow testing using different ranks of coal, and for the future testing of dry coal pumps. All PWR test hardware (piping, valve, and instrumentation) and the Cold Flow Test Facility structural tower will be left in place at the conclusion of the current test program so that the facility can be subsequently modified for long duration dry solids pump testing. Potential facility modifications will include: (1) installation of a high discharge-pressure dry solids feed pump, (2) a high pressure recycle gas compressor and storage tank, and (3) electrical facility upgrades for continuous operation of the dry solids pump and gas compressor. Additional government or private funding will be required to conduct the follow-on activities.

RESULTS AND DISCUSSION

The program will test two types of dried pulverized coal: (1) a high rank high volatile A bituminous coal dried to less than 6 wt% moisture, and (2) a lower rank lignite or sub-bituminous coal dried to less than 18 wt% moisture.

Testing will demonstrate uniform flow splitting (with flow split non-uniformities below 2 %RSD) and plug-free operation in a number of short-duration (4 minute) blow down tests. Test results will be reported in a subsequent Test Report.

CONCLUSION

The PWR ultra-dense phase multi-element injector and feed system is an enabling technology for the fabrication and operation of future low cost coal gasifiers. The EERC test facility and PWR hardware is an excellent location for developing this feed system at near commercial (3,000-tons/day – 31.5-kg/sec) scale. Following uniform flow splitting and plug free operation, this facility will be capable of further demonstrating continuous operation by the inclusion of a dry solids feed pump and recycle compressor.

LIST OF FIGURES

Figure 1. 400-Ton/Day Ultra-Dense Phase Feed System and Multi-Element Injector

Figure 1a. 400-Ton/Day Ultra-Dense Phase Feed System Flow Diagram at EERC (Batch Mode)

Figure 2. 1x18 Two Tier Multi-Element Injector (Drawing 7R110700A1)

Figure 3. Conical Injector Chamber (Drawing 7RE6392)

Figure 4. Injector Chamber Forward Closeout Flange (Drawing 7R110740)

Figure 5. The 1x6 Multi-Element Injector (Drawing 7R110701A1)

Figure 6. Pressurization Hopper/Tank Assembly (Drawing 7R109703)

Figure 7. 1,000-gal Atmospheric Silo (Drawing 7R109632)

Figure 8. Drop Down Pipe Sub-Assembly (Drawing 7R109726)

Figure 9. 700-gal High Pressure Discharge Tank (Drawing 7RE6393)

Figure 10. Tank Valve Spool Sub-Assembly (Drawings 7R109718)

Figure 11. Primary 2-1/2"Sch.160 Feed Line (Drawing 7R109703)

Figure 12. 1-1/4"Sch.XX Injector Discharge Dump Line (Drawings 7R109704, 705, & 706)

Figure 13. 7-Orifice Cascade Pressure Letdown Nozzle (Drawing 7R109740)

Figure 14. Ultra Dense Phase Flow Test Facility at EERC

Figure 15. Test Stand Elevation and Plot Plans – Southwest Corner of Building (PWR Drawings 7R109700, 701 & 702 or UNDEERC Drawing 010406drh-version2000)

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ACRONYMS AND ABBREVIATIONS

CA	California
CGE	Cold Gas Efficiency
EERC	Energy and Environmental Research Center
GN2	Gaseous nitrogen
HHV	Higher Heating Value
ID	Inside Diameter
MN	Minnesota
ND	North Dakota
NTIS	National Technical Information Service
P&ID	Piping and Instrumentation Drawing
PWR	Pratt & Whitney Rocketdyne
UND	University of North Dakota