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Conceptual Design of an Ultra-Dense Phase Injector and Feed System

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 design of an ultra-dense phase multi-element injector and feed system for use on PWR gasifiers operating at pressures to 1,000 psia. For the design of this injector and feed system, the pulverized coal's Bingham fluid yield stress is approximately 11 Pascals (Pa) with a coefficient of rigidity of 10 centipoise (cp). These values are typical of earlier experimental testing conducted with dried pulverized coal below 18 wt% moisture -- see, e.g., Sprouse and Schuman (1983, 1986). Each individual injector element is designed for a coal flow rate between 3 and 4 tons/hr (0.76 to 1.0 kg/sec) at full flow conditions. Hence, a small 400 to 500 tons/day (4.2 to 5.25 kg/sec) gasifier will require a 6-element injector, a 1,500 tons/day (15.7 kg/sec) gasifier will require an 18-element injector and a 3,000 tons/day (31.5 kg/sec) gasifier will require a 36-element injector. These injectors and feed systems are capable of "turn-down" below 50% of full-flow operation.

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EXECUTIVE SUMMARY

This document describes the technical work performed on the ultra-dense phase multi-element injector and feed system between May 2005 and March 2006. This feed system design effort is part of the work package for Task 2 (Injector and Feed System Development and Test) which leads to: (a) construction of a 400 tons/day (4.2 kg/sec) ultra-dense phase feed test facility at the University of North Dakota's (UND's) Energy and Environmental Research Center (EERC), Grand Forks, ND; (b) fabrication of a 400 tons/day (4.2 kg/sec) multi-element injector and feed system, (c) installing the injector and feed system into the EERC facility, and (d) cold flow testing the injector and feed system at pressure.

Under the current contract, the feed system will be tested under short duration (5 minute) batch mode conditions. However, provisions in the EERC facility are included for the subsequent installation of a continuous dry pulverized coal solids pump and recycle GN2 compressor for achieving long duration (i.e., life) test data in a follow-on program.

Two multi-element injectors were designed during this period: 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).

The eventual PWR feed system will take dried pulverized coal (at less than 18 wt% moisture and nominally 70 wt% passing 200 mesh screen) from an atmospheric pressure coal storage silo, pump it to approximately 1,200 psia for subsequent delivery into the 1,000 psia multi-element coal injector. Further details on this design are provided in the following pages.

EXPERIMENTAL METHODS

1.0 INTRODUCTION

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.

Unlike most rocket engine fuels which behave as Newtonian fluids, pulverized coal (at void fractions below 57 vol% whereby all solid particles are in direct contact with one another) is better characterized as a Bingham plastic [Perry and Chilton (1973)] which will plug whenever the shear stresses along the feed systems interior surfaces drop below the Bingham fluid's yield stress. To mitigate this problem, gasifier feed system designers typically operate these feed systems at void fractions significantly in excess of 57 vol% so that the Bingham fluid yield stress is entirely eliminated. However, these higher void fractions prevent the use of "rocket style" multi-element rapid-mix injectors by causing significant flow splitting non-uniformities and low single element mixing efficiencies. The unique characteristics of the feed/injector system design enable uniform feed at ultra-dense phase conditions (void fractions below 57 vol%) which facilitates the use of higher efficiency multi-element rapid-mix injectors.

The necessity for ultra-dense phase multi-element injectors and feed system can be shown in the mixing efficiency curve of Figure 1 – see, Sprouse (2005). To achieve rapid uniform mixing, fast reactant heat-ups, high injector end temperatures, and rapid reaction rates; rocket engine experience has shown that the single element Rupe mixing efficiency needs to exceed 90%. The Elverum-Morey group number in this figure is essentially a momentum ratio term between the reactants along with an orifice area modification that optimizes at about 3.0 for pulverized solids and gas. The subscript "coal" denotes the pulverized solids (and its carrier fluid – e.g., nitrogen, carbon dioxide, synthesis gas, etc.) while the subscript "stox" denotes the gas reactant (nominally an oxygen and steam mixture). For further definition regarding Rupe mixing efficiency and the terms within the Elverum-Morey parameter, see Sprouse (2005).

Figure 1 was developed from experimental data under ultra-dense phase coal feeding conditions and coal injection orifice inside diameters (IDs) between 0.2 and 0.3-in. (5 and 7.6 mm). It was generally found that the curve in Figure 1 is shifted vertically downward under dilute phase (void fractions above 80 vol%) coal flow conditions. Although the Elverum-Morey group number does provide an area ratio dependency, it can also be expected that the curve will be shifted significantly downward for injectors whose coal orifice IDs exceed values in excess of 2.0-in. (51 mm).

Modeling of gasifiers using multi-element rapid mix injectors shows the advantages gained in reducing overall gasifier size. Figure 2 is a typical result with Illinois #6 coal showing the gasifier's space residence time to be less than 0.5 second for 100 wt% carbon conversion at a nominal 82% cold gas efficiency (CGE – higher heating value, HHV, basis). This figure was developed from a detailed computer model by Sprouse (1980) and Sprouse and Schuman (1981). As a comparison, commercial gasifiers operating without multi-element rapid-mix injectors (such as Royal Dutch Shell's and General Electric's Texaco gasifiers that rely on large internal recirculation zones for temperature suppression) require space residence times on the order of 3 seconds. As seen in Figure 2, multi-element rapid-mix injectors produce an essentially 1-dimensional highly turbulent plug flow reaction condition within the gasifier that minimizes internal recirculation in order to achieve very high flame temperatures approaching 5,800 F (3,480 K) near the injector face.

It is this background that provides the basis for the design of an ultra-dense phase multi-element injector and feed system for use on steam/oxygen coal gasifiers. Such feed systems have the potential to significantly lower gasifier size which in-turn leads to lower capital installed costs and lower operating costs (via significantly reduced mean-time to repair with higher on-stream availabilities).

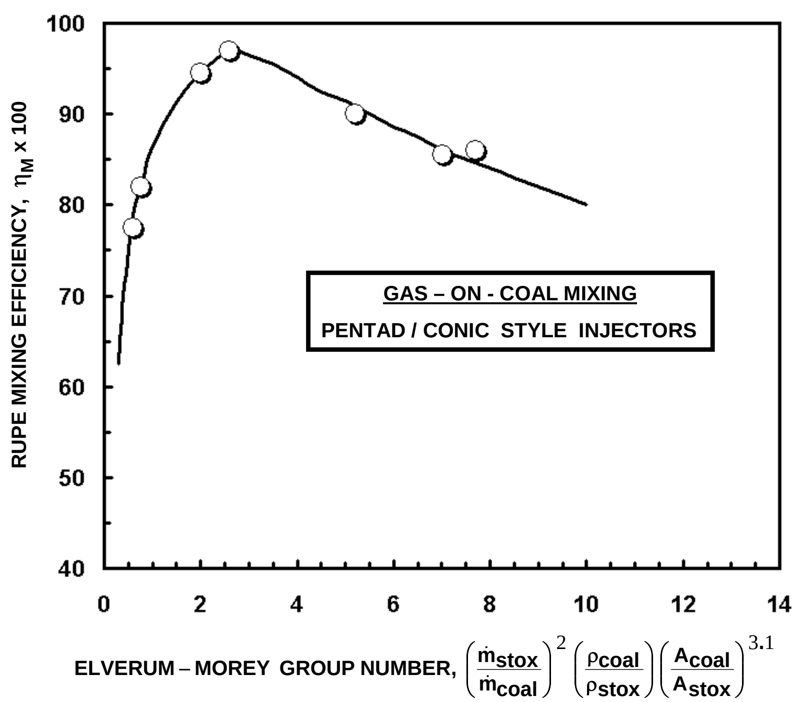


Figure 1. Single Element Rupe Mixing Efficiency For Rapid-Mix Injectors

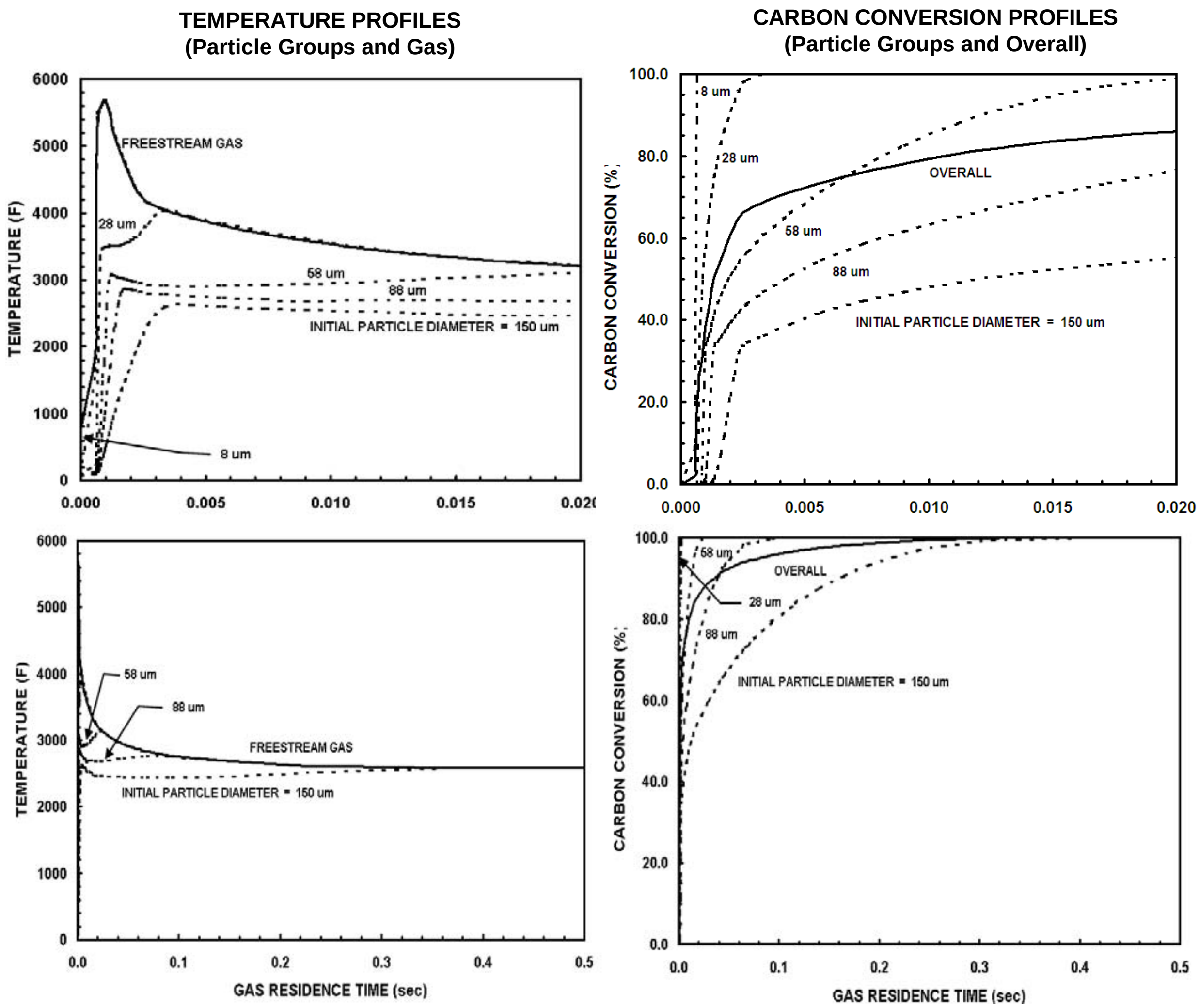


Figure 2. Multi-Element Rapid-Mix Injectors Produce Fast Gasifier Reactions and Short Residence Times (1-D Kinetic Modeling with Illinois #6 Coal)

2.0 FEED SYSTEM DESIGN

2.1. Base Feed System. The basic ultra-dense phase feed system design is shown conceptually in Figure 3. The feed system consists of: (a) an atmospheric pressure pulverized coal storage silo, (b) a high pressure discharge dry solids coal pump, (c) a high pressure discharge feeder tank, (d) a high pressure gas regulator system, (e) a multi-element rapid-mix injector, and (f) feed piping between the high pressure discharge tank and multi-element injector.

The atmospheric pressure storage silo is designed for receiving coal previously dried to less than 18 wt% moisture and pulverized to standard industrial grind conditions of 70 wt% passing through 200 mesh (74 μm) screen. From the bottom of the storage silo, the pulverized coal flows under the force of gravity into a high pressure discharge dry solids coal pump. A number of candidate coal pumps are currently being evaluated for this application.

Below the pump assembly is the high pressure discharge tank which includes a gas pressure regulation system. The gas pressure regulation system serves two purposes. First, it delivers the required gas volumetric flow rate into the coal bed to replace the gas volume lost by compression through the pump from 14.7 to 1,200 psia (0.1 to 8.27 MPa). Second, the regulation system is used to adjust the gas pressure within the discharge tank for trimming the solids flow rate to the injector. The actual solids flow rate is measured by Thermo-Electron Corporation (Minneapolis, MN) in-line flow meters. The flow rate signals from these sensors are sent to the gas pressure regulation system for trim.

Connected to the bottom of the high pressure discharge tank is the coal transfer line to the multi-element injector. The high pressure discharge tank, gas regulator, and transfer line assembly are adequately described by Oberg and Hood (1980). This part of the ultra-dense phase feed system was adequately tested by Friedman (1979), Oberg et al. (1982), and Combs (1982). This work established design criteria and requirements that have been incorporated into the current PWR design. The downstream multi-element injector subsequently distributes the solids flow into multiple streams (e.g., 3, 6, 18, 36, etc.) across the head-in of the gasifier for rapid-mix injection and reaction.

2.2. EERC Feed System. The EERC demonstration feed system was designed for a nominal coal flow rate of 400-tons/day (4.2 kg/sec). Under the current DOE cooperative agreement, the solids feed pump mentioned above was not included in the design for continuous operation. Instead, short duration batch testing at 4 minute durations are planned to be conducted as the initial step in hardware demonstration. The EERC test facility has been designed with a 15-feet (4.57-m) vertical separation distance between the atmospheric storage silo and the high pressure discharge tank to subsequently accommodate the solids pump in a later follow-on phase.

The Process Flow diagram for the EERC facility set-up is shown in Figure 4 with the Piping and Instrumentation Drawing (P&ID) given in Figure 5. The EERC test facility layout is shown in Figure 6. These figures include the balance-of-facility process piping downstream of the multi-element injector chamber. This equipment includes a cascade nozzle pressure letdown system, atmospheric cyclone separator and baghouse. Nominal flow rates are given in Figure 4.

The Figure 4 process flow diagram is essentially the same as the Figure 3 base feed system flow diagram with the exception of the atmospheric pressure cyclone separator and baghouse whose functions are to recycle the pulverized coal back to a 1,000-gal (264 liter) atmospheric pressure storage silo. The EERC cyclone and baghouse are expected to be provided by Donaldson Torit and contain rotary air lock valves manufactured by William M. Meyers & Sons. Based upon the flow rates shown in Figure 4, the baghouse is expected to have approximately 492 ft^2 (45.7 m^2) of filtration area and handle a nitrogen gas flow up to 1623 standard cubic feet per minute (scfm) – 46 m^3/min at standard conditions. The nitrogen gas exiting the baghouse will be sent to a stack and discharged into the environment. However, when the solids coal extrusion pump is added to the facility during the next phase, a recycle compressor will be added to the baghouse's discharge line in order to return the nitrogen back to the 700-gal (185 liter) high pressure discharge tank for continuous operation via the tank's regulator and upstream storage reservoir.

The Figure 5 P&ID shows all the valving and purge lines required for proper operation of the ultra-dense phase feed system at EERC. Since the multi-element injector (MEI) chamber is design to operate at pressures to 1,000 psia (6.9 MPa), the transport gas and pulverized solids must be returned to atmospheric pressure prior to entering the cyclone separator and baghouse. This pressure letdown system is comprised of a long length of 1-1/4-in. Schedule XXS pipe and a 5-element cascade pressure letdown nozzle assembly. The length of 1-1/4-in. piping was chosen to provide enough line pressure drop to increase the discharge flow's void fraction (within the 2-phase flow) from 55 vol% to approximately 85 vol% prior to entering the seven-orifice cascade letdown nozzle. The cascade letdown nozzle was sized for 2-phase solid/gas approach velocities of 150 ft/sec (45.7 m/s). The nozzle's carbon steel orifices are hardened to accommodate throat velocities on the order of 500 ft/sec (152 m/s). The sizing analyses for this nozzle's seven orifices were performed using Fisher Controls (1977) standard methods.

The Figure 5 P&ID shows two ball valves connected back-to-back at the bottom of the high pressure discharge tank. The added ball valve (BV-6) was required for safety reasons in the unlikely event that the main ball valve (BV-5) doesn't close at low coal level conditions within the high pressure discharge tank. At 1200 psia (8.3 MPa) discharge tank pressure, there is a good probably of damaging the cyclone and baghouse should the ultra-dense phase feed lines ever run out of pulverized solids with BV-5 opened.

Under normal shut-down conditions, purge valve SV-7 will always be opened as main ball valve BV-5 closes at the end of the run. Orificing on this purge line is sized to ensure that the purge gas' volumetric flow rate will be the same as the main ultra-dense 2-phase volumetric flow rate passing through ball valve BV-5. In the event the downstream feed line ever becomes plugged, ball valve BV-5 will be closed without opening purge valve SV-7 and the plug cleared by subsequent feed line disassembly. Opening purge valve SV-7 under plugged conditions, only serves to further compact the solids within the feed pipe making subsequent solids removal during feed line disassembly problematic.

The solids flow rate through the feed system will be determined during operation by the high pressure discharge tank's three load cells (MT-1, MT-2 and MT-3), static pressure transducer (PT-3), and pressurization gas flow meter (FT-1). Operational pressure drops across important feed line components will be measured by delta-pressure transducers DP-1, DP-2, DP-3, DP-4, DP-5, and DP-6. The upstream and downstream tap locations for these six delta-pressure transducers are indicated by the H and L designations after the transducer's number on the Figure 5 P&ID. Any pipe plug condition will be readily detected by any of the following instrumentation: the pressurization gas flow meter (FT-1), the tank load cells (MT-1, MT-2, and MT-3), or the injector's Thermo Electron Corp. in-line solids velocity meters (VT-1, VT-2, VT-3, VT-4, VT-5, and VT-6).

The main feed system elevations and plot plans are shown in Figure 6a. This feed system is operated within a high-bay enclosure over seven stories tall. The high pressure discharge tank and MEI conical chamber housing are supported by the beams of Level 2. The atmospheric coal silo and baghouse are supported by the beams of Level 5 while the cyclone and cascade nozzle are supported by the beams of Level 6. The structural support frames for these components are shown in Figure 6b. The high pressure discharge tank support frame is designed to float the high pressure discharge tank on three load cells (MT-1, MT-2, and MT-3) at equal 120-degree angular spacing. A small trench, approximately 5-ft (1.5 m) deep, will be dug below grade level to provide sufficient turn-around for the coal feed line exiting the bottom of the high pressure storage tank.

Feed system details for both the 1,000-gal (3.79-m^3) atmospheric pressure storage silo and 700-gal (2.65-m^3) high pressure discharge tank are shown in Figures 7 and 8. The top of the coal silo, Figure 7, contains four nozzles (N1, N3, N4, and N5). Nozzle N4 is the silo's primary fill nozzle during initial pulverized coal filling from EERC's existing pneumatic coal transfer system. Nozzle N5 is the silo's vent nozzle that connects directly into the baghouse for dust control. Nozzle N1 is designed to directly receive the recycle coal from the cyclone and baghouse during normal operation at 400 tons/day (4.2 kg/s). During all Phase 1 batch mode operations, only recycle coal from the cyclone will be directly fed back through nozzle N1. Recycle coal from the baghouse will be returned to the silo during post-test cleaning operations with the facility's pneumatic transfer system, as required.

At a 400-tons/day (4.2 kg/sec) rating, this EERC feed system is essentially commercial size for smaller gasification plants. It also represents a very good sub-scale test facility for subsequent commercial feed system design for larger 1,500 to 3,000-tons/day (15.7 to 31.5 kg/sec) plants. The EERC facility also has the capability of installing and testing next generation high pressure discharge dry coal extrusion pumps at near commercial scale in follow-on program phases.

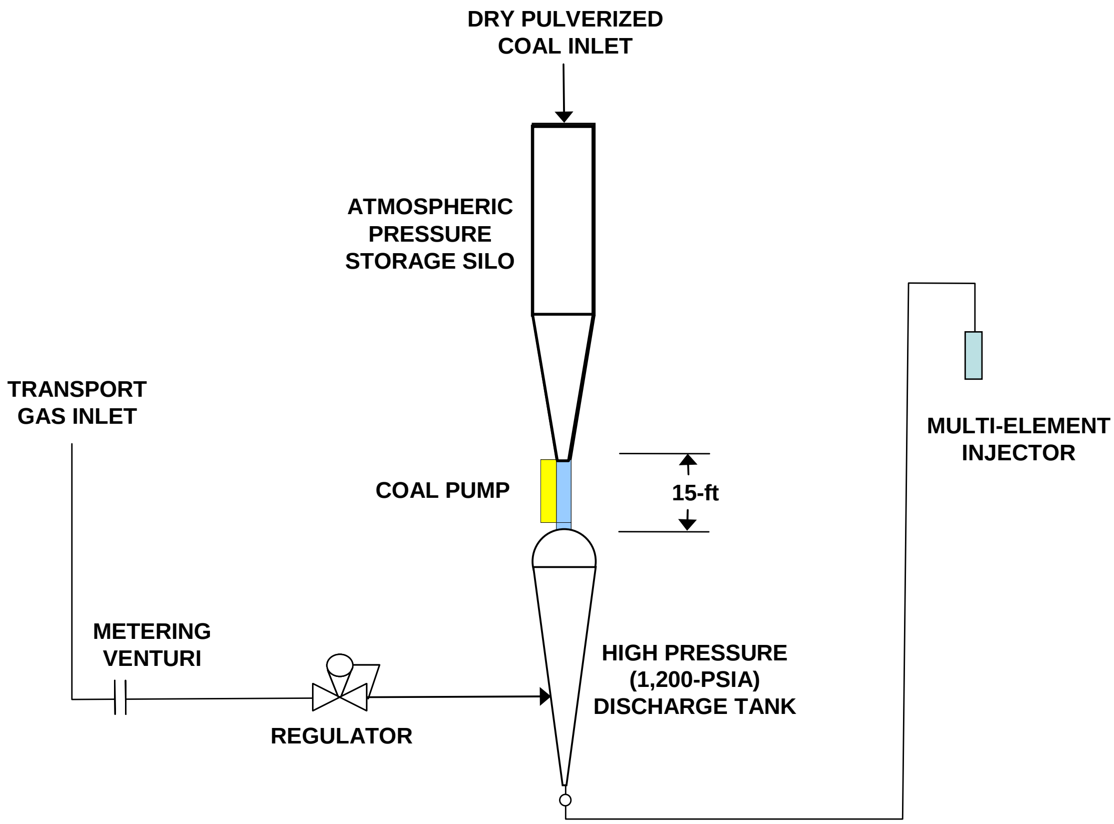
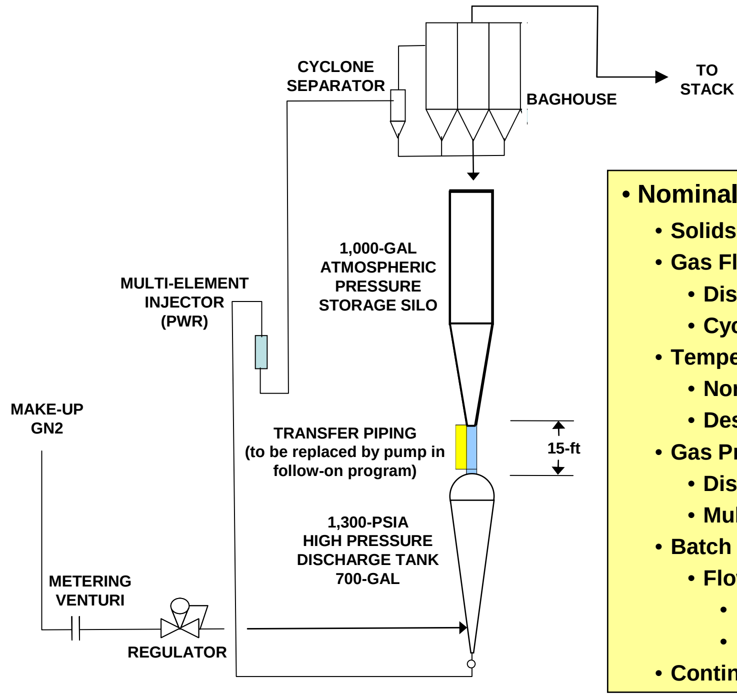


Figure 3. Flow Schematic of Ultra-Dense Phase Feed System



FLOW LOOP SCHEMATIC

- **Nominal Flow Requirements**
  - **Solids Flow Rate (lbm/sec): 9.26**
  - **Gas Flow Rates (lbm/sec)**
    - **Discharge Tank Inlet: 0.7 - 1.5**
    - **Cyclone Separator: 0.5 - 0.89**
  - **Temperatures (F)**
    - **Normal Operating: 50 - 80**
    - **Design: -20 to 150**
  - **Gas Pressures (psia)**
    - **Discharge Tank: 300 – 1300**
    - **Multi-Element Injector: 200 – 1000**
  - **Batch Operation – Phase 1**
    - **Flow Duration (minutes): 4**
      - **No Solids Pump**
      - **No Recycle Compressor**
  - **Continuous Operation – Phase 2**

Figure 4. EERC Process Flow Diagram

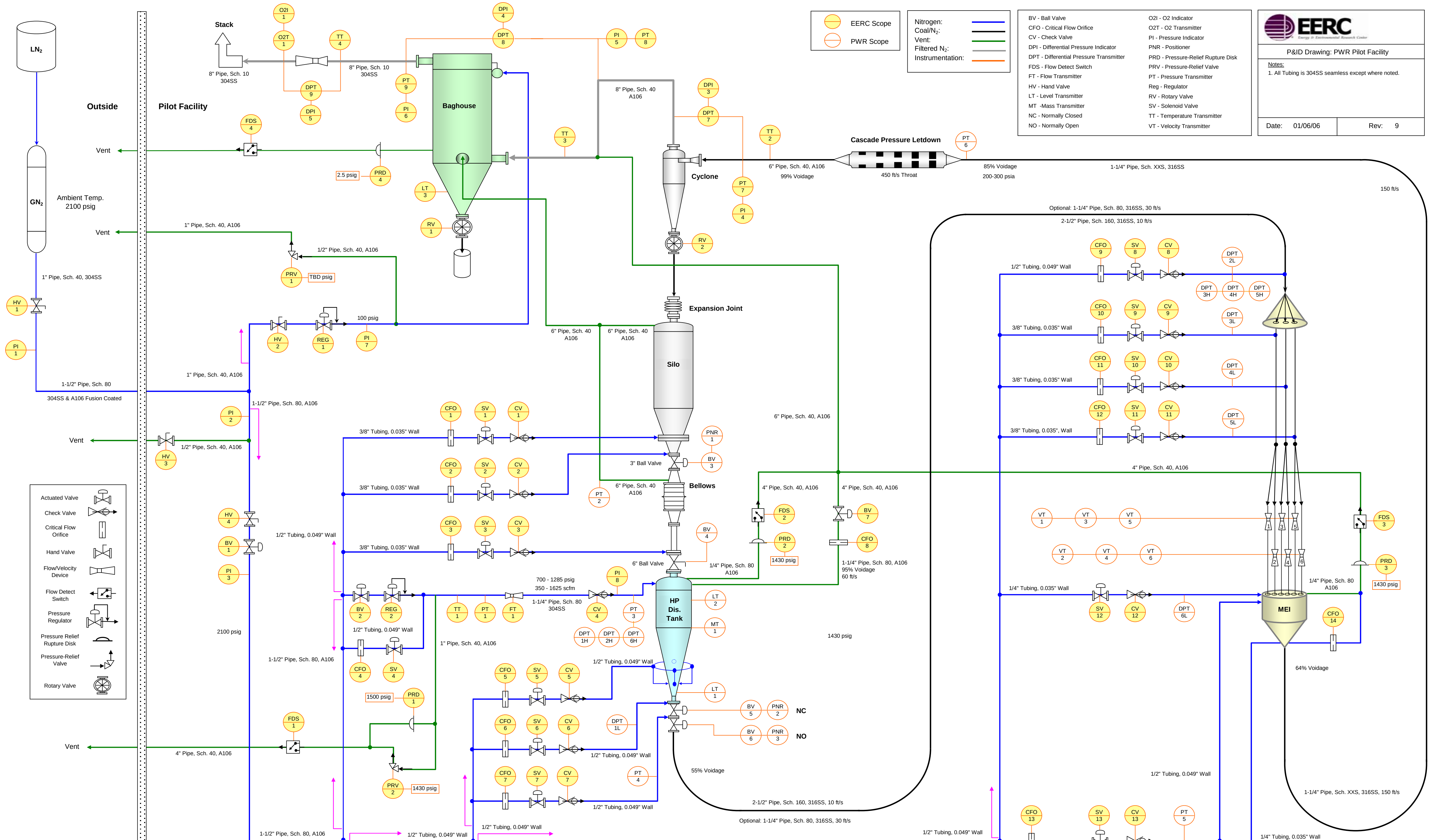
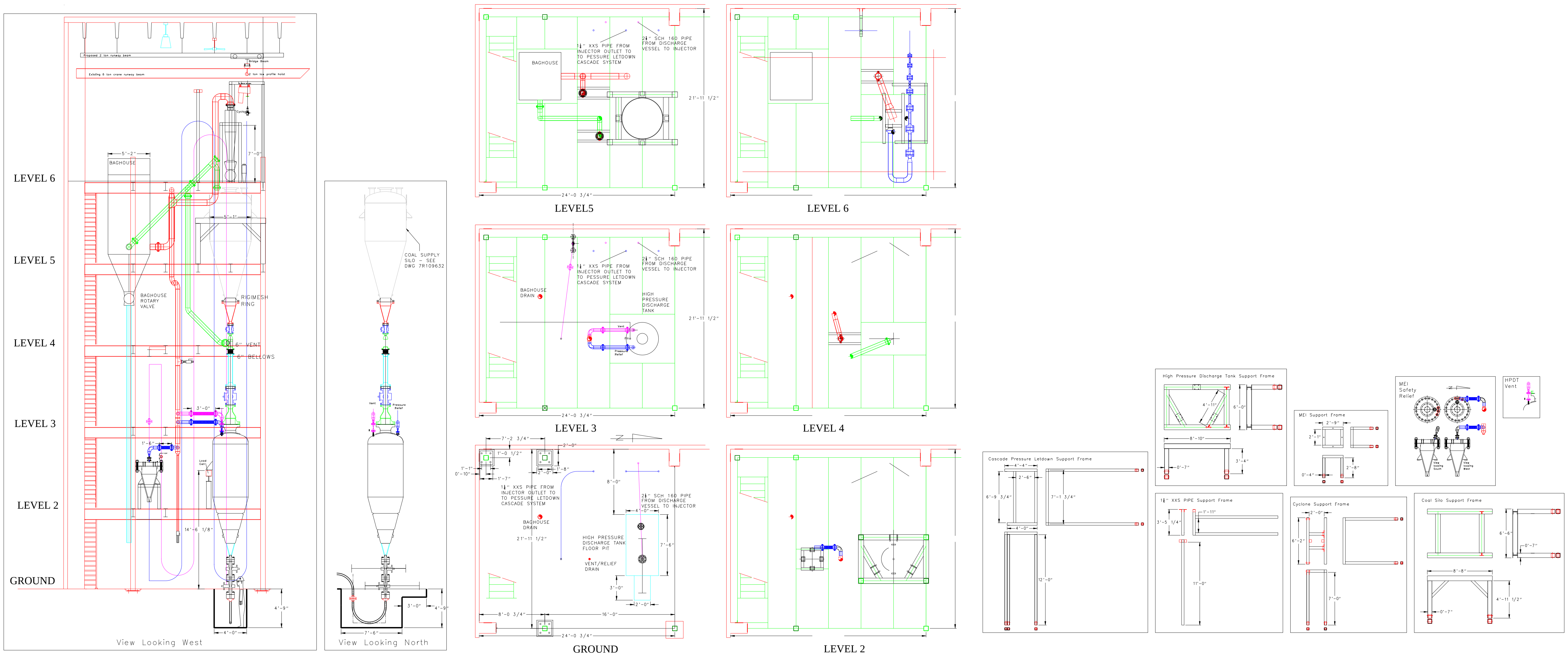


Figure 5. EERC Piping & Instrumentation Drawing (P&ID)



a) Elevations and Plot Plans

b) Steel Framing Details

Figure 6. EERC Test Facility Layout

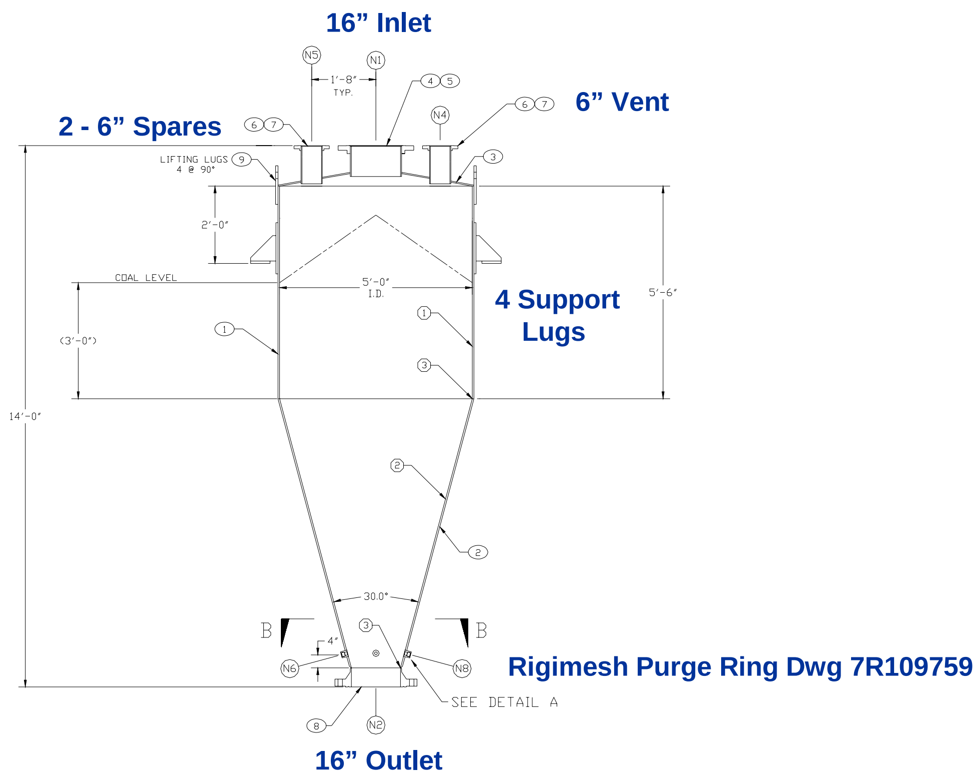


Figure 7. Atmospheric Pressure Storage Silo Details

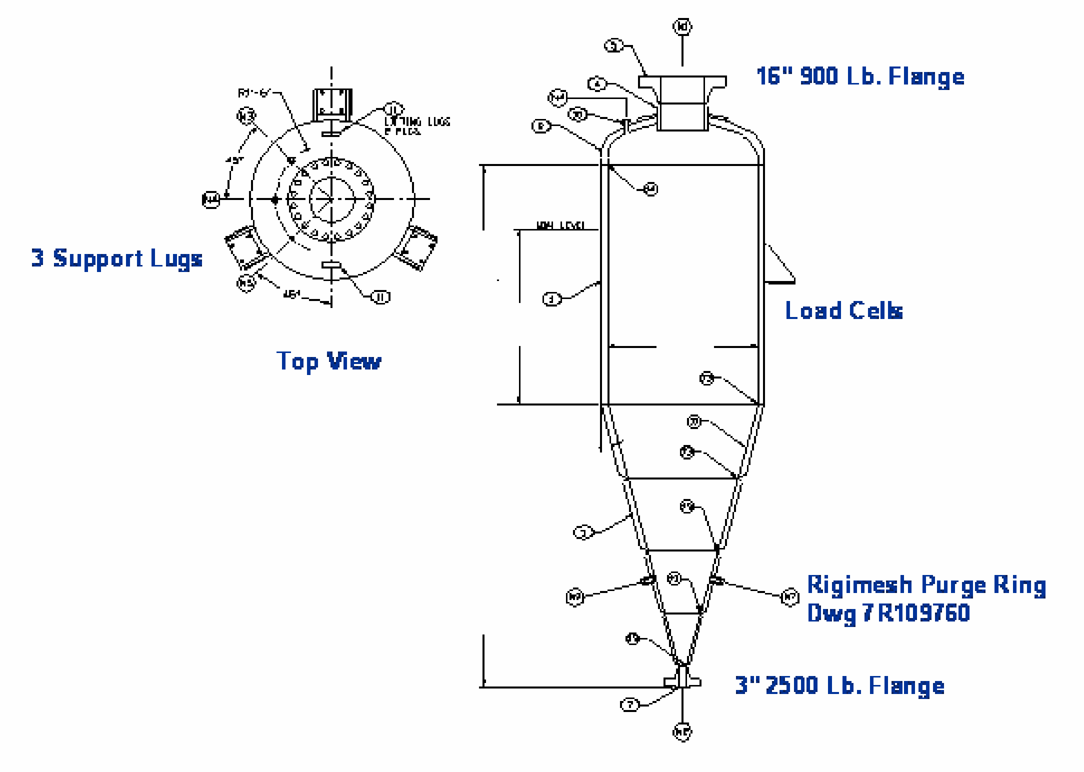


Figure 8. High Pressure Discharge Tank Details

3.0 INJECTOR DESIGN

Details of the multi-element injector designs to be fabricated and tested at EERC are provided in Figure 9 for the dual tier 1 x 18 split injector and Figure 10 for the single tier 1 x 6 split injector, respectively. Both cold flow assemblies use non-intrusive velocity flow meters for determining the uniformity of the multiple split streams. The design requirement for the coal split non-uniformity was established at less than 2.0 %RSD (relative standard deviation). The velocity sensors to be used are Ramsey Granucor DK13 sensors from Thermo Electron Corporation (Minneapolis, MN). The dual tier 1 x 18 split injector will run solid velocities at nominally 10 ft/sec (3.05 m/sec) while the single tier 1 x 6 split injector will run solids velocities at 30 ft/sec. Although the 1 x 6 split injector is essentially a 400 to 500-tons/day (4.2 to 5.25-kg/sec) injector, the 1 x 18 dual tier split injector design is rated for 1,200 to 1,500-tons/day (12.6 to 15.7-kg/sec).

For commercial scale capability up to 3,000 tons/day (31.5 kg/s), the forward tier 1 x 3 splitter (in the Figure 9 two tier design) will be replaced by another 1 x 6 splitter to produce a 36 element injector rated at 2,400 to 3,000-tons/day (25.2 to 31.5-kg/sec). This 3,000-tons/day (31.5-kg/sec) injector would scale by adding a third outer row of 18 elements to the injector's face.

The inlets of both injectors to be tested at EERC mate directly to the discharge of the 2-1/2-in. Schedule 160 feed pipe. At 400 tons/day (4.2 kg/s), the solids flow velocity of approximately 10 ft/sec (3.0 m/s) exiting the feed pipe is maintained through all legs and split tiers of the 1 x 18 injector splitter, Figure 9. For the single tier 1 x 6 injector splitter (Figure 10), the solids velocity is initially accelerated to approximately 30 ft/sec (9.1 m/s) before it enters the splitter element and remains at 30 ft/sec (9.1 m/s) throughout all injector legs and into the conical chamber housing. Static pressure tap locations are strategically located within the injectors to determine pressure drops across various legs. These injectors also include gas purge ports to aid post test removal of any unplanned solid plugs within the splitter elements.

Both multi-element injectors are designed for mating with the EERC injector chamber housing shown in Figure 11 below. The conical housing is 21.75-in. (553 mm) in diameter at its forward end to simulate a 1200 tons/day (12.6 kg/s) gasifier operating at 1,000 psia (6.9 MPa). The forward closeout blind flange contains 18 holes (drilled and tapped) for passing 3/4-in. tubing connected to this flange by standard Swageloc fittings. The inside diameter of these tubes are machined to 0.593-in. for matching the diameters of the smallest made Thermo Electron Corporation solids velocity meter. The forward closeout blind flange also contains the chamber’s static pressure tap and pressure relief port. The static pressure tap contains an integral porous filter to prevent plugging. The pressure relief port also contains a special contoured tap for solids plug prevention within the burst disk during rupture.

The chamber housing’s forward flange (i.e., the flange bolted to the closeout blind flange) also contains a nitrogen bypass purge system for increasing the solids void fraction within the chamber above the ultra-dense phase flow condition of approximately 55 vol%. The primary purpose of this bypass purge system is to help increase the pressure drop through the downstream pressure letdown system at lower injector operating pressures and solids flow rates. This nitrogen bypass system ensures that the volumetric gas flow rate through the atmospheric cyclone and baghouse is maintained at near constant operating conditions for all tests.

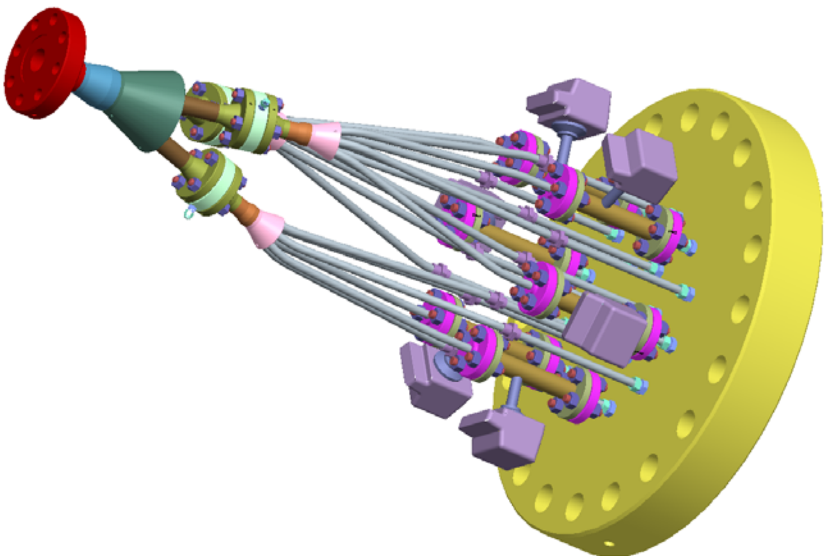


Figure 9. The 1 x 18 Feed Splitter Injector Assembly Design

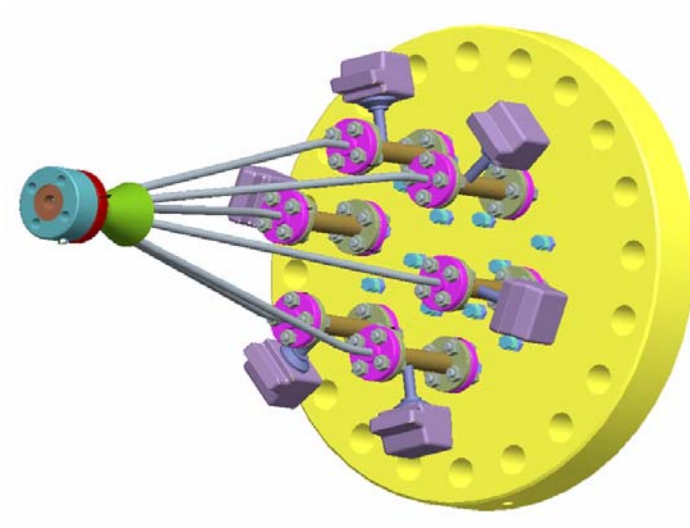


Figure 10. The 1 x 6 Feed Splitter Injector Assembly Design

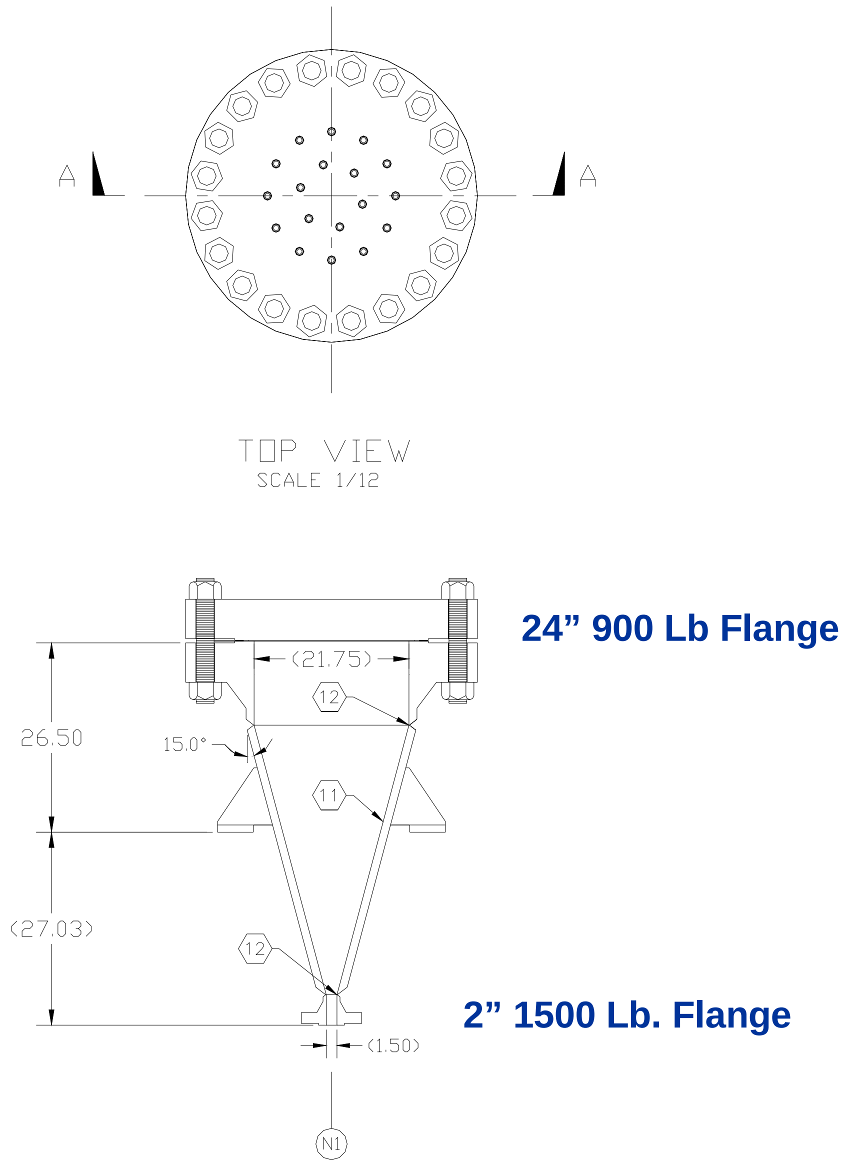


Figure 11. MEI Chamber Housing Detail

4.0 TEST FACILITY

The overall EERC test facility is shown in Figure 12. The facility shown in Figure 12 contains a number of coal gasification/combustion test bays for testing integrated systems as well as individual components. Perhaps the most extensive system being tested on this campus at the bench scale is DOE's flagship high efficiency fluidized bed transport gasifier.

For ultra-dense phase feed system commercial development, the test stand shown in Figure 6 will be erected within the southwest corner of the high bay building (the tall foreground building in Figure 12a). It will include all of the equipment identified in the Figure 5 P&ID above (for batch mode testing). Much of the facility infrastructure (e.g., GN2 supply, overhead crane, control room, data acquisition, vent stacks, experienced operating personnel, etc.) already exists. EERC is currently under a subcontract to complete the Figure 5 and 6 facility construction by the end of CY2006. Batch mode performance testing of the feed system and injectors are expected to begin by January 2007 and should be completed within a few months.

Facility upgrades for follow-on continuous life testing as shown in Figure 13 should be relatively straight forward. The only major equipment additions will be for the 1200 psia (8.3 MPa) gaseous nitrogen/air recycle system. Major equipment for this system should be: (1) a 0.9 lbm/sec (0.4 kg/s) recycle compressor, (3) a 6,000-gal (23,000 liter) GN2/air recycle storage tank, and (3) a 1200 psia (8.3 MPa) pressure regulator for the recycle storage tank. Other ancillary equipment will include: oxygen concentration monitors for the recycle storage tank, interconnect piping and compressor cooling circuits.

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

Figure 12. EERC Test Facility

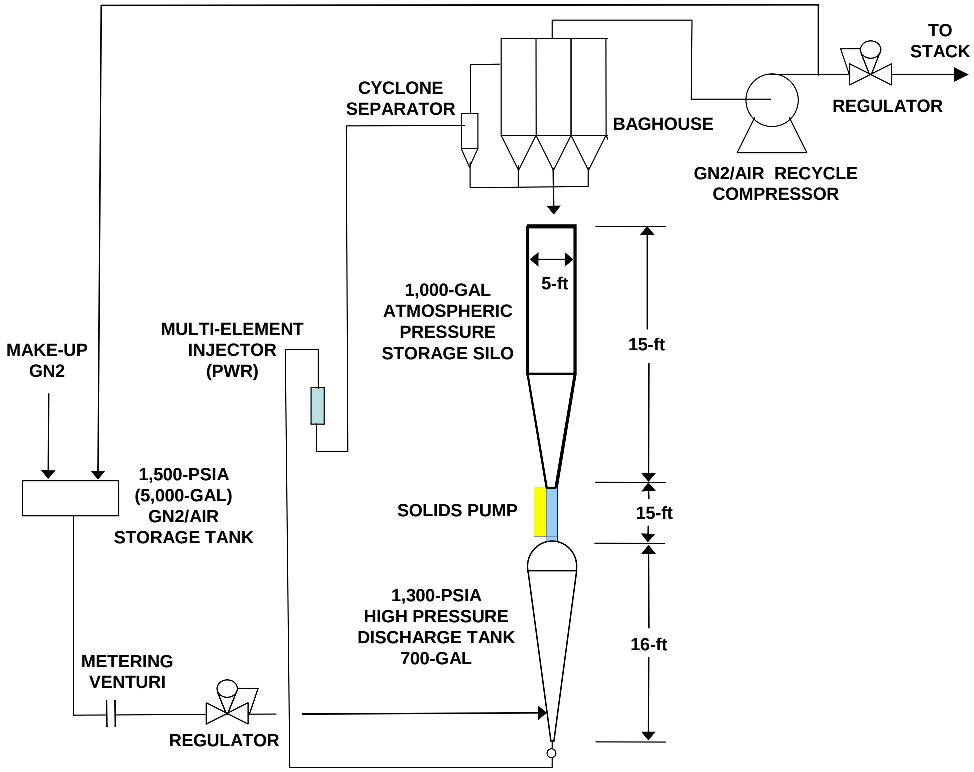


Figure 13. EERC Process Flow Diagram for Continuous Operation

RESULTS AND DISCUSSION

The critical design review (CDR) on the 400-tons/day (4.2-kg/sec) ultra-dense phase feed system described above was successfully completed in December 2005. PWR management approval was subsequently given to continue the task into the fabrication and construction phase. All drawings were finally released through the PWR metaphase process on March 3, 2006. The program currently envisions testing 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 is expected to 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. A draft test plan for this program has been written and is currently in review by PWR and EERC engineers and management. The test plan will be submitted to DOE-NETL as a Topical Report for review and approval. This test plan is expected to be finalized and formally released during the Spring of 2006. This document will detail the test matrix, success criteria, instrumentation plan, control, and start-up/shut-down operating procedures to be used during the test phase of this program.

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

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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