Linear Extrusion 400 Tons/Day Dry Solids Pump

TOPICAL REPORT

Reporting Period
Start Date: June 1, 2006
End Date: April 30, 2008

Principal Author
Kenneth M. Sprouse — Task Development Lead
David R. Matthews — Task Designer Lead

September 18, 2008

DOE Award Number

DE-FC26-04NT42237 (DOE NETL)

Task 5. Dry Solids Pump Development & Demonstration

Pratt & Whitney Rocketdyne, Inc.
6633 Canoga Avenue
P.O. Box 7922
Canoga Park, CA 91309-7922

DISCLAIMER

ABSTRACT

Pratt & Whitney Rocketdyne (PWR) has developed an innovative gasifier concept that uses rocket engine experience to significantly improve gasifier performance, life, and cost compared to current state-of-the-art systems. The PWR gasifier concept uses a compact and highly efficient (>50%) dry solids pump that has excellent availability (>99.5%). PWR is currently developing this dry solids pump under a U.S. Department of Energy (DOE) cooperative agreement. The conceptual design on two dry solids pumps were completed under this agreement and one pump concept was selected for preliminary design. A preliminary design review (PDR) of the selected pump was presented on September 20, 2007 to PWR management and numerous technical specialists. Feedback from the PDR review team has been factored into the design and a Delta-PDR was held on April 9, 2008.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

PWR has developed design concepts for two alternative linear dry solids extrusion pumps. One of these is based on a "rolling mill" concept and the other is based on a "tractor mill" concepts. Both of these designs are described briefly in this report.

The "tractor mill" design concept was selected to proceed with preliminary design. A preliminary design was developed for this pump and reviewed in a Preliminary Design Review (PDR). However, the details of this pump are proprietary and are not provided here.

An analytical model has been developed to assess pump performance and optimize design parameters. This model is described and sample results are presented. This model suggests that the PWR linear extrusion pump has the potential to achieve a dry solids mechanical pumping efficiency in excess of 50% when pumping dry solids to 1,200 psia gas discharge pressures.

A cold flow test facility has been constructed at the University of North Dakota's (UND's) Energy and Environmental Research Center (EERC -- Grand Forks, ND). This test facility will be used to test the dry solids pump developed on this program. This facility is described briefly and the key pump interfaces are summarized.

BACKGROUND

Various compact high-efficiency and high-availability dry solids pumps have been considered as possible replacement pumps to cycling lock hoppers for high gas-pressure discharge service (to 1,300 psia). Starting in the mid 1990's and continuing into 2007, the U.S. DOE funded Stamet Inc. to develop an extrusion feeder whereby the extrusion force to move the granular solids into a high gas pressure reservoir is supplied by the shear surface forces from moving wall boundaries rather than the centrifugal body forces of a high speed spinning vane as previously used in the Meyer et al. (1983) kinetic extruder device. This effort initially began as a demonstration program at a nominal 10-tons/day solids throughput to 300 psia gas discharge pressures, Aldred (2000). This effort eventually reached 530 psia discharge gas pressures in January 2005 -- see, e.g., Aldred and Saunders (2005) -- and is expected to eventually reach gas discharge pressures above 1,000 psia -- see, e.g., Aldred and Saunders (2006). Details of the basic Stamet dual disk extruder pump -- trademarked as the Posimetric™ Pump -- was first given by Firth (1991). Hay and Peterson (2001) have subsequently shown how this pump would be scaled to commercial solids throughputs using multiple dual-disks on a single rotor. In 2007, General Electric (GE) Corporation bought Stamet Inc. and has indicated -- Parent (2007) -- that further updates on the Posimetric™ dual disk pump technology will not be published for sometime.

Many technical factors are involved in optimizing dry solids pumps for commercial applications. Among the most important technical factors are: (a) mechanical pump efficiency, (b) compactness of design, and (c) pump on-stream availability. It can be expected that the pump which scores the highest on all three of these technical factors will also be the most economical pump in terms of manufacturing, operating and maintenance costs. Mechanical pump efficiency plays a major factor in operating costs. It has been reported by Sprouse et al. (2006) that the isentropic work, W_{isen}, required to pump a granular material into a high gas-pressure reservoir can be calculated from the following equation

$$W_{isen} = \frac{(P_d - P_{atm})}{\rho_s (1 - \varepsilon)} \qquad (1)$$

where the variable P_d is the gas pressure at the discharge reservoir, P_{atm} is the gas pressure at the pump's inlet (usually atmospheric conditions of 14.7 psia), ρ_s is the true solids density of the coal (usually about 90 lbm/ft^3), and ε is the void fraction of the solids bed within the atmospheric storage silo (usually about 55 vol% for most granular solids at standard industrial grind conditions of nominally 70 wt% passing thru 200 mesh, 74-µm opening, screen). Hence, Equation 1 can be used to show that the minimum (isentropic) work required to pump a given mass of coal to 1,200 psia gas discharge pressure is approximately 6 kJ/lbm (kilojoules per pound mass). Thus for a standard 3,000 tons/day gasification plant, this means that the minimum power consumption for pumping coal to 1,200 psia is about 417 kW (kilowatts). In reality, the power requirements are much higher due to the low mechanical efficiencies found in the dry solids coal pumps developed to date.

The mechanical pump efficiency, η, is defined by the following well known equation:

$$\eta = \frac{W_{isen}}{W_{act}} \qquad (2)$$

where the variable W_{act} is the actual work consumed by the pump in discharging the granular solids into the higher gas-pressure reservoir. For example, using the formulas of Equations 1 and 2, Sprouse reported that the mechanical pump efficiency for a pair of cycling lock hoppers, η_{lh}, can be determined by the following relation:

$$\eta_{lh} = \frac{\eta_c\,(\gamma-1)(1+\varepsilon)\left(1 - \frac{P_{atm}}{P_d}\right)}{n\,\gamma\left[\left(\frac{P_d}{P_{atm}}\right)^{\gamma-1/n\gamma} - 1\right]} \qquad (3)$$

where the variable γ is the ratio of specific heats of the gas being used to pump the solids, the variable n is the number of stages in the compressor used to compress the gas that is pumping the solids, and η_c is the mechanical efficiency of the gas compressor. From Equation 3 is can be shown that the mechanical pump efficiency for a pair of cycling lock hoppers operating at 1,200 psia discharge gas pressures is about 25% when using a 4-stage compressor having a compression efficiency of 85% with a pump gas having a ratio of specific heats of 1.4. Thus for a standard 3,000 tons/day gasification plant, the actual power consumption for pumping coal to 1,200 psia will be about is about 1.7 MW (megawatts) when using lock hoppers.

For comparison at 1,200 psia discharge gas pressures, the Lockheed kinetic extruder pump -- Meyer et al. (1983) -- will achieve mechanical efficiencies of only 40% due to the fact that this pump makes no attempt to recover its angular kinetic energy. In testing reported by Aldred and Saunders (2005 and 2006), the GE Posimetric™ extrusion pump has only achieved mechanical efficiencies of about 5% to date -- although higher solids flow rates and revised discharge system designs are expected to provide significant improvements in this number.

Regarding compactness, both alternate extrusion pumps described above are much smaller than cycling lock hopper systems -- which in addition to large high pressure operating tanks need either: (a) large baghouses to filter the pumping gas prior to atmospheric discharge, or (b) large atmospheric storage gas reservoirs if this discharge gas is to be recycled.

Due to significant erosion issues, the availability of these alternate extrusion pumps is not well known. None of the pumps have accumulated over 700 hours of total operation and all of the pumps have required significant servicing over the course of their testing. Even though cycling lock hoppers are considered commercially available pumps (with low erosion), there appears to be no cycling lock hopper pumping system in operation today at 1,200 psia discharge gas pressures. This appears due to the fact that reliable 1,200 psia dusty-gas valves capable of 30,000 open/close cycles (nominal 1-year mean-time-between-maintenance, MTBM) have not yet been demonstrated.

LINEAR EXTRUDER DRY SOLIDS PUMP CONCEPTS

The extrusion solids pumps of Lockheed and GE-Stamet appeared (on first impression) to have the simplest mechanical design and most compactness of all the dry solids pumps initially considered. The main problem with these pumps was their demonstrated low mechanical efficiency. However, previous PWR dry solids transport experience in ultra-dense phase (whereby solids stresses carried within the granular media can be significant) appeared to indicate that improvements to these designs could be achieved -- particularly in terms of increased mechanical efficiency. It is believed that a linear extrusion process whereby the solids flow through the pump is essentially in a straight (i.e., axial) direction -- as opposed to the curve-linear (i.e., circumferential) direction of the Lockheed and GE-Stamet pumps -- can produce relatively high mechanical efficiencies by the elimination of high speed angular kinetic energy loss (the Lockheed design), or high inter-particle frictional shearing and solids pressure flow stagnation losses (the GE-Stamet design). The solids flow rate for the first linear dry solids extrusion pumps will be at 400-tons/day solids to be consistent with the EERC test facility flow capacity for continuous operation.

In the 1970-80's, PWR observed that if a given length of tube (or pipe) was initially filled with a granular solid at ultra-dense phase (compacted) void fractions (nominally 55 vol%) and then instantaneously pressurized at one end, the tube would remain plugged without solids flow over an extended period of time. Eventually, as the high pressure gas permeated through the packed solids bed (causing the gas pressure to rise within the downstream side of the plug), the solids would finally begin to blow out of the downstream end (i.e., the atmospheric pressure side) of the tube. Hence, the basic idea behind the PWR linear extruder dry solids pump concepts is to design a plugged pipe with moving walls. The length of the pipe and the speed of its moving walls are determined on the basis of preventing gas flow from moving backwards through the moving plug (i.e., no leakage) and ensuring that there is sufficient wall friction to prevent this plug from blowing out. The permeability of the moving solids bed and the effective hydraulic diameter of the pipe channel (which may be rectangular in cross-section) are also key design parameters in ensuring successful pump operation. One should note that a linear extrusion pump having parallel moving walls has the potential of achieving mechanical pumping efficiencies approaching 100%.

The Linear Dry Solids Extrusion Model

The model used in determining performance of the linear extrusion dry solids pump was taken from Sprouse and Schuman (1983 and 1986). For a linear dry solids extrusion pump with relatively slow moving walls, the inertial terms in the momentum equations can be removed -- which greatly simplify the remaining equations to be solved. If one were modeling the Lockheed kinetic extruder pump, Meyer et al. (1983), these terms would need to be retained within the model. The solids constitutive relations used in the linear dry solids extrusion model are found in the "Solids Stress Tensor" Supplementary Materials Section of Sprouse and Schuman (1983) -- which can be obtained directly from the *AIChE Journal*, New York, for a nominal fee).

Two methods were used during the program for solving the model's equations on a high speed digital computer. The first method involved the use of the Rocketdyne Elliptic Analysis Code for Turbomachinery (REACT). This is a PWR proprietary code which has a very good unstructured grid generation capability for handing exotic geometrical wall boundary profiles. After many months of programming and debugging, this numerical method was unable to successfully converge on any flow field solution. The formulation was found to be numerically unstable. The reason for this numerical instability appeared to be the hyperbolic nature of the two solids stress field equations (i.e., the equilibrium stress equation and the Mohr-Coulomb compatibility relation). Since the REACT formulation is heavily dependent upon elliptic equations, the dominance of the hyperbolic stress equations appeared to be a major problem with numerical convergence.

The second numerical method used was a method-of-characteristics (MOC) formulation to take advantage of the hyperbolic nature of the stress field equations. This model was successful in converging on both gas (velocity and pressure) and solids (velocity, and compressive and shear stress) flow field spatial solutions. However, additional work with the MOC computational fluid dynamics (CFD) model still needs to be completed before it can adequately handle the exotic geometrical wall boundary profiles of the rolling-mill linear dry solids extruder pump described below.

The MOC CFD model shows (Figure 1) the expected axial gas pressure profile within the extrusion channel for an extrusion pump operating at 1,200 psia discharge gas pressures. In Figure 1, the pump inlet is at Non-Dimensional Vertical Position 4.0 and the exit is at 0.0. The pressure is seen to decay from the pump's exit to atmospheric pressure conditions within half the length of the extrusion channel for the baseline pump design. Faster wall speeds were shown to produce higher gas pressure-decay gradients whereby the gas pressure remained atmospheric closer to the belt/scraper interface. In all cases there was no leakage of gas from the upstream side of the pump's channel. All gas initially trapped within the solids bed at the pump inlet was subsequently discharged into the high gas pressure reservoir.

The MOC CFD model gives the gas velocity, v_g, within the extrusion pump's channel to be determined by the simple algebraic relation:

$$v_g = \frac{v_y(0)}{P}\left\{P_{atm} - (P_d - P_{atm})\exp\left[-150\left(\frac{1-\varepsilon}{\varepsilon}\right)^2 \frac{\mu\, v_y(0)\, L}{P_{atm}\, D_p^2}\right]\right\} \qquad (4)$$

where the variable $v_y(0)$ is the average solids velocity in the pump, L is the length of the pump's extruder section, μ is the dynamic viscosity of the gas trapped within the intertices of the coal particles within the pump, D_p is the effective particle diameter of the solids within the pump, and P is the local gas pressure within the pump's extruder section. Both the gas velocity and gas pressure are one-dimensional in this MOC CFD model and depend only upon the axial location within the pump. This is not true of the solids stress and velocity fields to be discussed later which are two-dimensional. Figure 1 and Equation 4 show that the gas velocity is effectively equal to the solids velocity at the pump's inlet and is only a fraction of the solids velocity at the pump's exit where that fraction is given by the gas pressure ratio, P_{atm} / P_d.

The gas permeability coefficient, ϕ_p, of a packed solids bed is a key parameter for the linear extrusion dry solids pump design and is defined by Perry and Chilton (1973) as:

$$\phi_p = \frac{\varepsilon}{150}\left(\frac{\varepsilon\, D_p}{1-\varepsilon}\right)^2 \qquad (5)$$

where the gas permeability coefficient ϕ_p is usually given in the units of the Darcy -- i.e., 1.0 darcy = 1.0 μm^2 = 1.0 ml·cp/atm·s·cm (or 1.0 milliliter-centipoise per atmosphere per second per centimeter).

Equations 4 and 5 show that smaller effective particle sizes and bed void fractions lead to significantly lower permeability coefficients and hence shorter pump lengths. The effective particle size is also a function of the tortuosity and particle shape within the solids bed. Sprouse and Schuman (1983) reported that the effective particle size D_p for use in the above relations is the volume-diameter mean, D_{31}, of the nominal particle size distribution. Perry and Chilton (1973) recommends use of the Sauter mean diameter, D_{32}, for determination of the gas permeability coefficient. For standard industrial grind particle size distributions (i.e., 70 wt% passing through 200 mesh, 74-μm, opening screen), both D_{31} and D_{32} will usually be found to be in the 20-μm size range. At nominal ultra-dense phase void fractions of 55 vol%, Equation 5 shows the expected value of the permeability coefficient ϕ_p to be around 3.0-darcy.

It was found when first exercising the MOC CFD model that a permeability coefficient of 3.0-darcy was too high when scaling the published Stamet Posimetric™ dual disk pump results from Aldred and Saunders (2005). Hence, the high gas pressure gradient at the pump's exit must be either: (a) compacting the solids bed to lower void fractions, (b) changing the numerical coefficient in Equation 5 [based on mono-spherical particles, Bird et al. (1960)] to larger values, or (c) effectively reducing the particle diameter by increasing the bed tortuosity. The gas permeability coefficient, ϕ_p, from Equation 5 was therefore reduced to be consistent with the reported Posimetric™ data for all MOC CFD modeling runs conducted to date. It was also seen that this lower gas permeability coefficient, ϕ_p, is consistent with those values previously reported by Lockheed Missiles & Space Co. (1979) in permeability testing with the centrifugal kinetic extruder pump. It is expected that extensive permeability testing under high bulk solids pressure loading will also be performed with candidate solids during the next phase of the pump design to determined the actual permeability coefficient, ϕ_p, and ensure an adequate extrusion pump length, L. Based upon these results, the length of the pump's moving wall will be sized to ensure good pump feeding performance for a range of particle size distributions realizing larger particles will require longer pump lengths.

The lower than originally expected permeability may also be due to the following reason. As mentioned above, the numerical coefficient of 150 is for mono-spherical particles. Perry and Chilton (1973) show a number of correlations that increases this coefficient for non-spherical shapes -- however, none reduce the permeability the required order-of-magnitude. Hence, it would appear the pump's bulk solids pressures (e.g., 400 psi) are breaking off some particle edges into smaller shapes that subsequently fill voids and create more tortuosity at somewhat lower void fractions. Generally speaking, significant fracturing of the particles within the bulk solids is not expected to occur until bulk solids pressures in excess of 2,000 psi are reached which will significantly lower the particle size distribution via pulverization. Such ultra-high bulk solids pressures are undesirable since they will significantly reduce the pump's mechanical efficiency.

In addition to extrusion pump modeling with the continuum mechanics approach of Sprouse and Schuman (1983 and 1986), the developing field of granular dynamics (GD) -- see, e.g., Theuerkauf et al. (2007) -- may someday also be a viable modeling alternative. Limitations with this method -- for extrusion pumps feeding standard industrial grind size particles (whose basic building blocks are nominal 8-μm size spheres) -- are the billions of particles required to be tracked during the computation. Today's high speed computers with extensive parallel processing architectures are still not fast enough to produce results within reasonable times. Most GD modeling efforts to date have been focused on large granular flow through atmospheric bins and screw feeders where the particle size is 1/4-in. and there are no high gas pressure-gradient interactions with the solid particles. In any event, some GD modeling could be performed as an aid in developing the theoretical underpinnings for the material solids properties used in the continuum mechanics models -- e.g., the internal friction angle, ϕ; the effective wall friction angle, ϕ_W; the coefficient of cohension, c; the alignment of the solids stress and strain rate tensors; and the void fraction compressibility relation (among other things).

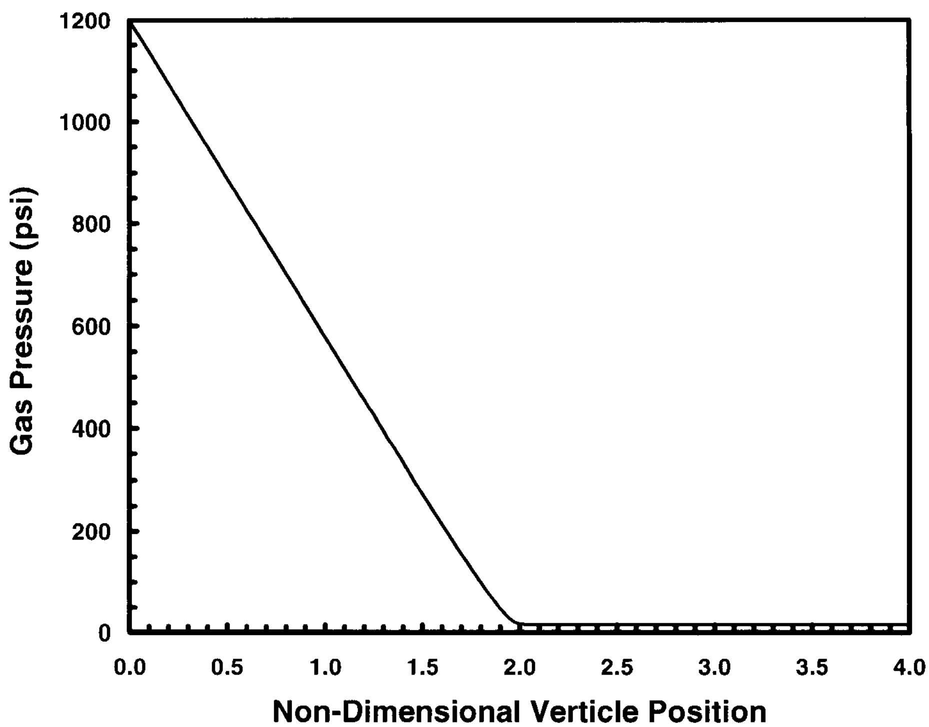

Figure 1. Extrusion Element Gas Pressure Profile From Model

Rolling-Mill Linear Dry Solids Extrusion Pump Design

The first 400-tons/day linear dry solids extrusion pump concept was based upon a patent pending rolling mill design due to its relative mechanical simplicity -- see, Sprouse and Matthews (2006). The main extrusion pump element is shown in Figure 2. It consists of eight rollers on each of two moving walls. The moving walls can either be parallel or slightly converging in the axial flow direction. At the top of the rolling mill sub-assembly is the pump's inlet that is directly connected to an atmospheric coal storage silo. At the bottom of the rolling mill sub-assembly, the extruded coal passes through a blocking valve (here identified as a cylinder valve) -- the extruded coal stream being dimensionally smaller than the rectangular opening in the valve's cylinder. Below the blocking valve is a fast acting flapper valve to prevent catastrophic blow-back should the coal plug within the rolling mill's extruder section lose frictional contact.

An upper view of this pump (Figure 3) shows the motor and gear reduction box sub-assemblies for driving the extrusion pump element. Each gear box is designed for a single shaft input at 1720 rpm and an eight shaft output that is required for driving the moving walls within the pump.

Figure 4 shows an angled cut-away view of the entire pump assembly -- although it should be noted that the axis of the pump assembly is always in the vertically downward direction. This cut-away view shows a high pressure breaker (e.g., hammer) mill downstream of the flapper valve followed by a short expansion bellows to provide compliance between the pump and high pressure discharge tank (HPDT) that are rigidly fixed to the same structural steel framing. The size of the high pressure breaker mill is dependent upon the degree of particle sintering that has taken place in the upstream extrusion pumping element. Based upon the work reported by Aldred and Saunders (2005), it is expected that any sintering should be minimal so the porous retaining plates located downstream of the breaker mill's rotor can be removed to minimize solids hold-up above the mill.

Since the REACT code was incapable of convergence, a mechanical 2-phase fluid flow analysis of the rolling mill dry solids extrusion pump was not completed under the current DOE cooperative agreement. Furthermore, the backup MOC CFD computer code was not completed in time for subsequent modification to handle the high inter-particle shear/slip zones around the complex roller contours. It can be expected that these zones will produce significant inter-particle frictional loses and hence cause lower mechanical pumping efficiencies than possible with a straight moving wall design. Without an adequate CFD model of the linear rolling mill dry solids extrusion pump, it was decided that an alternate extrusion pump design be further investigated that has the inherent features of higher mechanical efficiency due to less inter-particle friction loses -- i.e., a straight moving wall design.

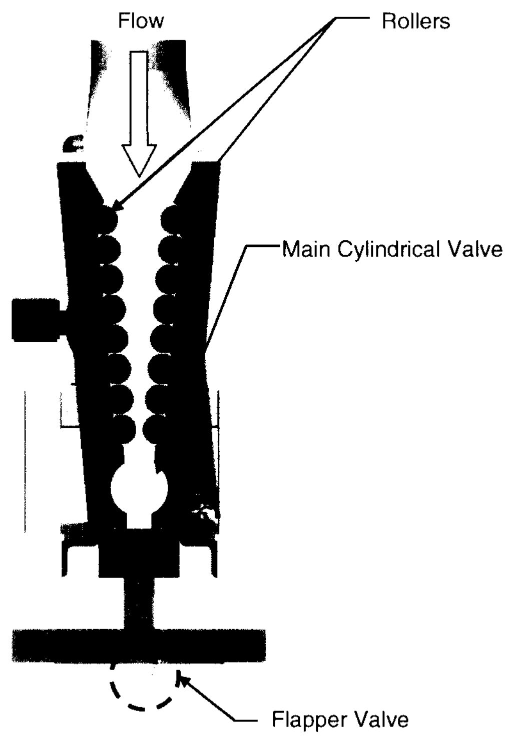

Figure 2. Rolling Mill Linear Extrusion Pump Element

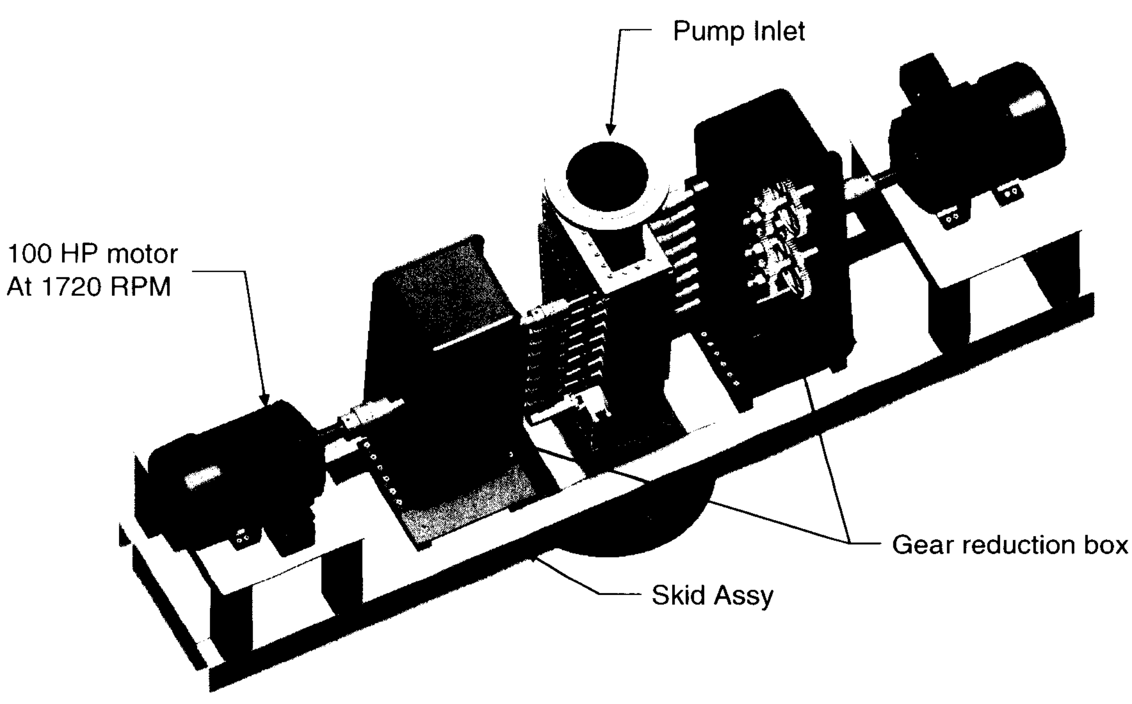

Figure 3. Upper View of Rolling Mill Linear Extrusion Pump

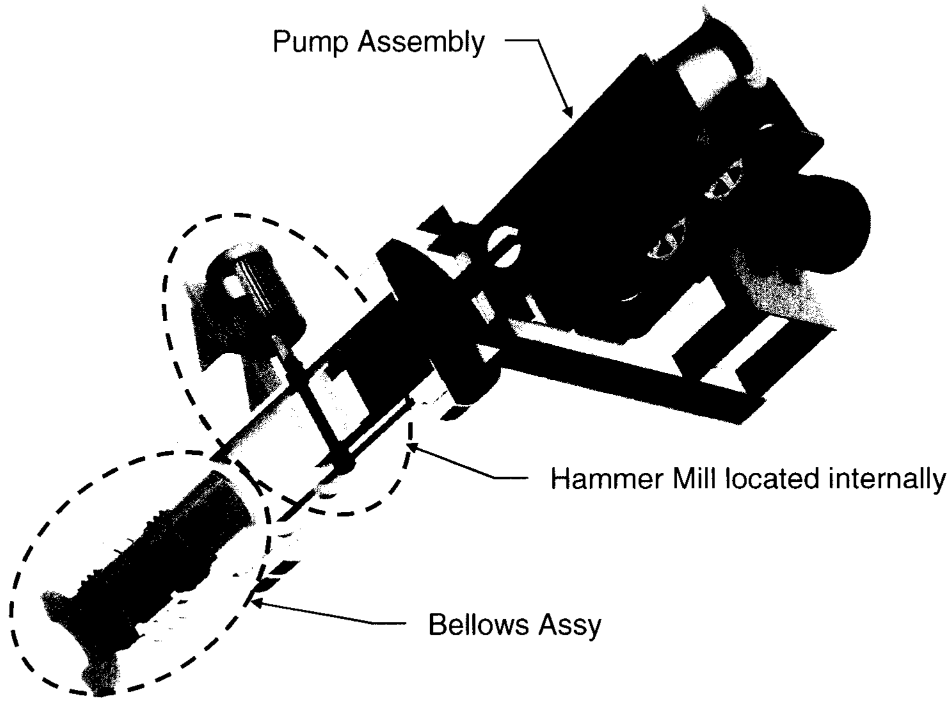

Figure 4. Overall Layout of Rolling Mill Linear Extrusion Pump

Tractor-Mill Linear Dry Solids Extrusion Pump Design

A second patent pending 400-tons/day linear dry solids extrusion pump concept was developed based upon a straight moving track design which eliminates most of the high inter-particle friction zones of the rolling mill described above -- see, Sprouse and Matthews (2008). The overall tractor-mill linear dry solids extrusion pump layout is similar to that shown in Figure 4 with the exception of the rolling-mill sub-assembly being replaced by a sub-assembly having smooth moving parallel walls followed by a short scraper section upstream of the cylinder blocking valve. An external layout view of the tractor-mill linear dry solids extrusion pump is provided in Figure 5. One will note the use of much simpler gear reduction boxes that have a single shaft output as opposed to the eight shaft output on the rolling-mill extruder design.

As mentioned above, the detailed MOC CFD model was successful in determining extrusion element performance for the tractor-mill design. The mechanical efficiency of the extrusion element itself was found to be over 80%. The solids velocity flow field was also found to be in uniform plug flow until the solids reached a step in the stationary scrapper near the end of the moving tractor belt. At this location, significant inter-particle slip occurs with some recirculation patterns developing near the scraper's exit.

The solids stresses at the walls of the moving belt and scraper are given in Figure 6. The shear stress along the channel wall (both stationary scraper and moving belt), $\tau_{xy}(\text{wall})$, was found to rapidly increase from zero at the pump's exit to a relatively high value at the scraper/belt interface. At this location, the shear stress instantaneously switched signs to a negative value and then decayed back to zero approximately 3/4-ths of the distance of the overall channel length. The actual power consumed by the pump, $\dot{W}_{act}$, is found by multiplying the local value of this shear stress by the local wall velocity and integrating this result over the wall length. It is this value that is subsequently used in Equation 2 to determine the mechanical pumping efficiency.

The remaining solids stresses given in Figure 6 are for the various tensile loads exerted on the channel walls. Here, the standard sign convention for these tensile stresses is used which indicates that all wall loads are compressive (i.e., having negative numerical values). The stress $\sigma_x(\text{wall})$ is the solids pressures exerted on the walls of the stationary scrapper and moving belt. Like the shear stress, this pressure was seen to rapidly rise from zero at the pump's exit to a very high value at the scraper/belt interface and then decay back to zero approximately 3/4-ths of the distance of the overall channel length. The stress $\sigma_y(\text{wall})$ is the effective solids pressure in the pump's axial direction along the channel walls. In a non-converging channel, this solids pressure will only be seen on the leading edge (or nose) of the scraper. The stresses $\sigma_z(\text{wall})$ and $\sigma_z(\text{centerline})$ are primary pressures acting on the pump's non-moving end-plates at the plate/belt interface and at the center of the channel respectively. All of the above loads were subsequently used in sizing the pump's internal components (e.g., scraper, belts, bearings, structural supports, etc.) to ensure hardware integrity.

Following a conceptual design review (CoDR) on November 30, 2006; the tractor-mill linear extrusion pump was selected by PWR management for further development into a preliminary design. A detailed preliminary design review (PDR) on this pump was held on September 20, 2007. Both CoDR and PDR briefing packages are PWR proprietary documents. These documents show the evolution of the 400-tons/day linear tractor-mill design and provide detailed results of the pump's stress analyses, CFD performance analysis, materials selection analyses, manufacturability and cost analyses, Quality Assurance (QA) analyses, and Failure Mode and Effects Analyses (FMEA) -- among other things.

During the PDR, a number of action items (AIs) were given to the team for resolution during the detailed design phase of the tractor-mill linear extrusion pump. Although most of these AIs are relatively minor concerns, PWR management did request that the team provide a detailed assessment of other pre-1990 dry solids pumps that were previously considered as cycling lock hopper replacements. These previous designs were discussed in detail at the April 9, 2008 Delta-PDR.

Action items directly related to the design of the linear tractor dry solids extrusion pump included (among others): (a) development of lab/bench scale risk mitigation tasks; (b) exploring alternate motive tractor belt concepts and bearings; and (c) changing from a wet to a dry sump for particulate removal behind labyrinth seals. Post PDR analyses provided resolution to most of these AIs. Lab/bench scale risk mitigation testing tasks are currently being defined and their hardware designed.

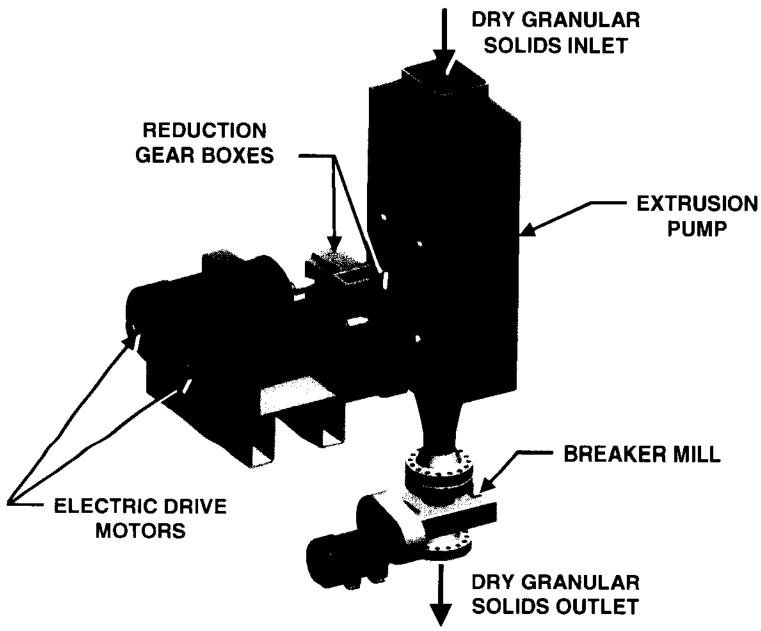

Figure 5. Tractor-Mill Linear Dry Solids Extrusion Pump Layout

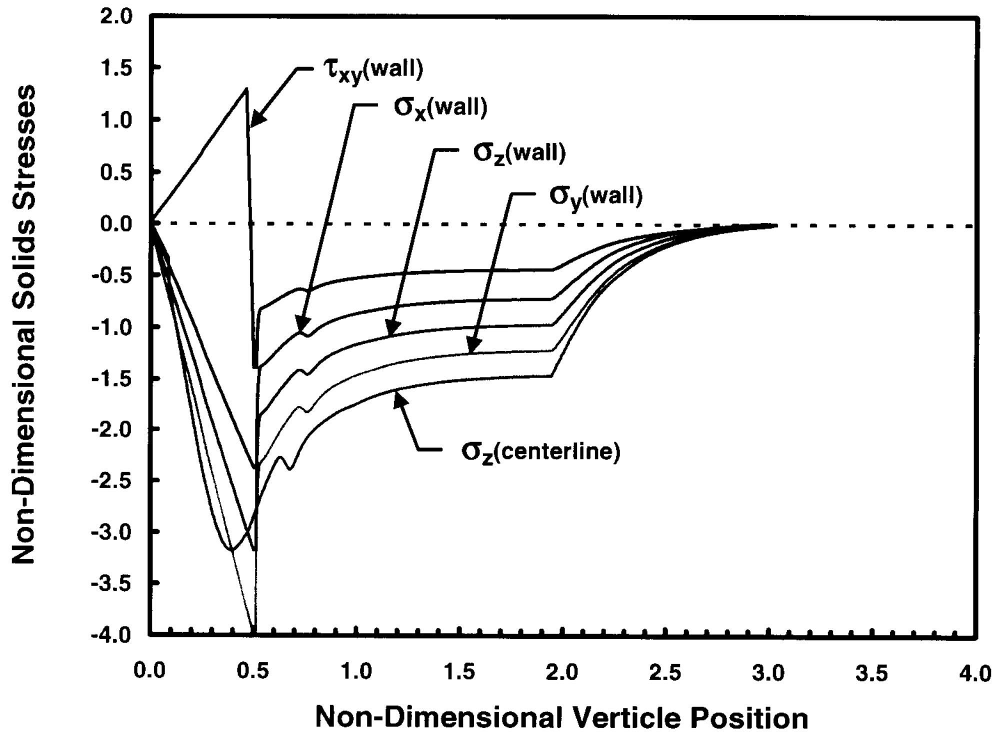

Figure 6. Solids Stresses on Tractor-Mill Walls From MOC CFD Model

Test Facility and Solids Pump Interface Requirements

The test facility at EERC for pump performance and long-duration endurance-life testing is shown schematically in Figure 7. This facility is currently being used to study high pressure (to 1,000 psia) ultra-dense phase solids transport from the HPDT and through various multi-element injectors that will be attached to the head-end of PWR compact gasifiers. These tests -- currently conducted in short (4-minute) batch mode operation at 400 tons/day solids flow rates -- are reported by Sprouse, et al. (2007 and 2008). For dry solids pump testing, EERC will remove the 15-ft of interconnecting pipe between the atmospheric silo and HPDT for subsequent installation of the dry solids pump. In order to conduct continuous testing, EERC will also install the high pressure recycle gas compressor and all ancillary electrical wiring, mechanical piping (including regulators and receiver tank), and instrumentation and control devices. It is expected these changes will be incorporated for the start of dry solids pump testing in early 2010. Pictures of the EERC test facility as it exists today (without the dry solids pump and recycle compressor) is shown in Figure 8. The coal silo and HPDT are located in the pictures' foreground along with the 15-ft of interconnecting pipe to be removed.

In order to accommodate a 400-tons/day dry solids pump, the EERC test facility has been designed to meet the general pump/facility interface requirements of Table 1 within the 15-ft of vertical run between the bottom of the 3rd floor (top of HPDT) and the middle of the 4th floor (bottom of silo) in Figure 8. Table 1 shows the total installed pump assembly weight requirement on the test stand to be below 15-tons. However, the lifting capacity on the EERC overhead bridge/crane is limited to 3-tons. Hence, the weight of each individual pump component within the overall assembly (i.e., extruder element, gear reduction boxes, motors, breaker mill, stand mounting fixtures, etc.) must be below this bridge/crane limit to prevent the added expense and time of renting cranes during assembly.

Table 1 further shows that either air or nitrogen can be used as the solids ultra-dense phase transport gas for continuous long duration testing in order to save on nitrogen gas make-up costs. When air is used as the transport gas, Table 1 indicates that the carbonaceous feedstock (e.g., coal) must be replaced by an inert solids feedstock such as sand or mixed metal silicates. Finally, the pump inlet and exit piping interfaces are standard 16-in. American Society of Mechanical Engineers (ASME) 300 and 900-lb flanges, respectively.

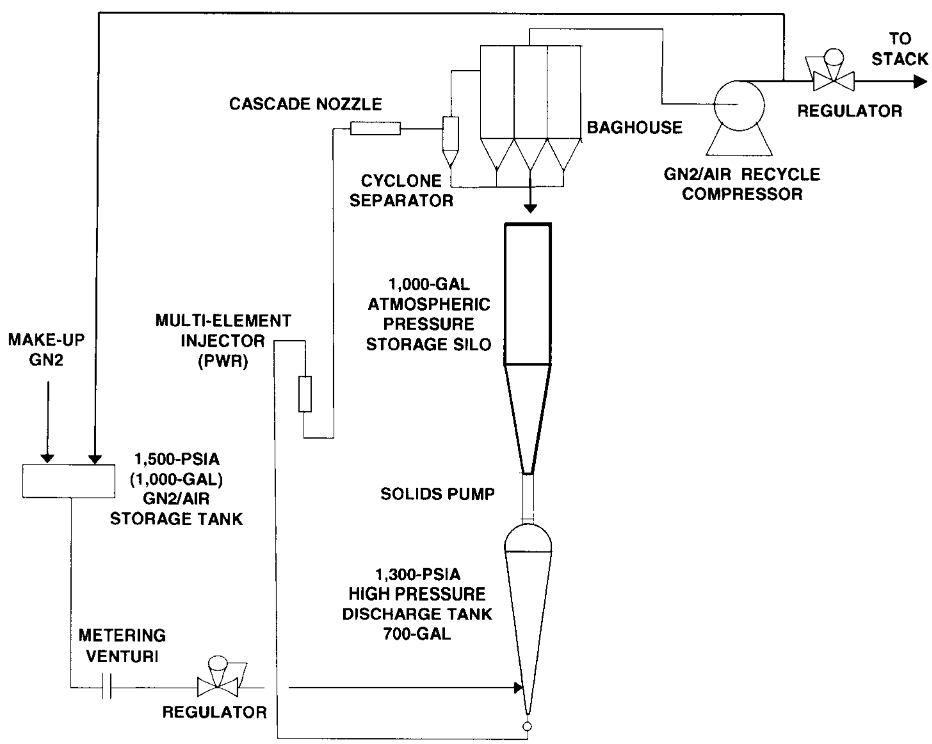

Figure 7. EERC 400-Ton/Day Ultra-Dense Phase Feed System Flow Diagram

TOWER 5TH FLOOR SOUTH VIEW

TOWER GROUND FLOOR SOUTH VIEW

Figure 8. EERC Six-Story Tower Test Facility

Table 1. Pump/Facility Interface Requirements Summary

Solids Flow Rate, tons/day (lbm/sec):	400 (9.26)
Gas Flow Rate (lbm/sec)	0.01
Operating Temperature (F):	-20 to 150
Inlet Gas Pressure (psia):	14.7
Max. Discharge Gas Pressure (psia):	1,300
Nominal Gas Composition (vol%):	
Nitrogen:	79 to 98
Oxygen:	2 to 21
Pulverized Solids Inlet Conditions	
Solids Bulk Density (lbm/ft^3):	40
Void Fraction (vol%):	55
Solids Moisture (wt%):	2 to 15
Solids Ash Content (wt% dry)	
Carbonaceous Solids:	9 to 11
Sand and mixed metal silicates:	100
Particle Inlet Size Distribution	
Maximum Particle Size, mm (in.):	2.0 (0.079)
wt% thru 70 mesh (210 µm):	< 99.0
wt% thru 200 mesh (74 µm):	< 70.0
Pulverized Solids Discharge Conditions:	Same as Inlet Conditions
General Facility Interface Parameters	
Overall Height (ft):	< 15
Inlet/Outlet ASME Flange Sizes:	16" – 300# & 900# (resp.)
Inlet/Outlet Horizontal Offset (in.):	< 40
Overall Weight (tons):	15 to 20
Electrical Supply Requirements	
Line Voltage (Volts):	460 to 480
Number of Phases:	3
Frequency (Hz):	60
Overall Power Consumption (kW):	< 200
Pump Structural Design Safety Factors (per ASME)	
Ultimate (BPVC Section II Part D Appendix 1):	> 3.5
Yield (BPVC Section II Part D Appendix 1):	> 1.5
Fatigue (BPVC Section VIII Division 2 Appendix 5):	see Figs. 5-110.1 thru 5-110.4

Reliability, Availability and Maintainability (RAM) Requirements

As noted in the introduction, successfully developing a dry solids extrusion pump includes more than designing a pump with high mechanical pumping efficiency and compactness. Successful development also includes high levels of reliability, availability and maintainability (RAM). It is expected that the main driver in obtaining high RAM marks is how best to manage coal particle erosion and wear on main mechanical component surfaces and ancillary seals. Erosion management may include the use of highly abrasion resistant metals and ceramics or the extensive use of gas purging to prevent solids contact and accumulation in critical pump locations.

Based upon the current state-of-the-art of commercially available cycling lock hopper pumps (e.g., those found in various Royal Dutch Shell coal gasification facilities) and the alternate replacement pump work previously funded by DOE (as mentioned above), the mean-time-between-maintenance (MTBM) requirement for the linear dry solids extrusion pump has been set at 1-year. The requirement for the mean-time-to-remove-and-replace (MTRR) a linear dry solids extrusion pump on an operating facility will be 24-hours. And finally, the mean-time-for-shop-overhaul (MTSO) requirement of a linear dry solids extrusion pump has been assigned the target value of 2-weeks.

Using these numbers, it can be shown that the overall expected dry solids pump availability (with one replaceable spare unit) is 99.5%. As expected, this availability number and its component factors (MTBM, MTRR, and MTSO) were critically debated at the September 20, 2007 PDR -- with a number of AI's directed towards sub-scale validation testing of erosion wear rates prior to the completion of detailed design.

CONCLUSION

The current efforts conducted to date indicate that a compact linear dry solids extrusion pump can be developed having mechanical pumping efficiencies greater than those previously demonstrated by Lockheed (40% -- the kinetic extruder) and GE-Stamet (5% -- the Posimetric™ dual disk extruder). The target extrusion mechanical efficiency for the linear dry solids extrusion pump is 50% or greater (at least twice the maximum efficiency of a cycling lock hopper system discharging into 1,200 psia gas pressures). Current MOC CFD modeling has shown that the mechanical efficiency within the pump's extrusion channel (not including motor, gearbox, and breaker mill losses) is over 80%. However, the AIs submitted at the September 20, 2007 PDR show that a number of sub-scale risk mitigation tests need to be completed during detailed design in the areas of solids permeability, wall friction and erosion to better ensure that the final pump design can meet its primary design requirements (discharge gas pressure, solids flow rate, mechanical efficiency, geometrical envelope, and RAM). Finally, PWR management has requested that another look be directed at those high (70%) mechanical efficiency pumps that were heavily supported by DOE in the 1970-80's during this country's last oil/energy crises. This review was completed during the April 9, 2008 Delta-PDR and showed the significant advantages of the PWR linear tractor design.

LIST OF FIGURES

REFERENCES

Aldred, D.L., *Proof of Principal Test to Feed and Meter Granular Coal into 450 psig Gas Pressure, Final Report*, FG26-98FT40330-06 (DE00784619), National Technical Information Service (NTIS), Springfield, VA (2000).

Aldred, D. and T. Saunders, “Successful Continuous Injection of Coal Into Gasification and PFBC System Operating Pressures Exceeding 500 psi – DOE Funded Program Results,” paper 47 (Session 38) presented at the *22nd Annual International Pittsburgh Coal Conference*, University of Pittsburgh, PA (2005).

Aldred, D. and T. Saunders, “Development of a Coal Feeder for Continuous Injection into Gasification Operating Pressures of 1000 psi -- DOE Funded Phase III Program Review," paper 49-2 (Session 49) presented at the *23rd Annual International Pittsburgh Coal Conference*, University of Pittsburgh, PA (2006).

Bird, R.B, W.E. Stewart and E.N. Lightfoot, *Transport Phenomena*, Wiley, New York, NY (1960).

Firth, D., "Multiple-Choke Apparatus for Transporting and Metering Particulate Material," U.S. Patent No. 4,988,239 (1991).

Hay, A.G. and R.L. Peterson, "Multiple Channel System, Apparatus and Method for Transporting Particulate Material," U.S. Patent No. 6,213,289 (2001).

Lockheed Missiles & Space Co., *Coal Feeder Development Program, Phase III Final Report*, FE-1792-61, National Technical Information Service (NTIS), Springfield, VA (1979).

Meyer, J.W., J.H. Bonin, and A.D. Daniel, "Kinetic Extruder -- A Dry Pulverized Solid Material Pump," U.S. Patent No. 4,376,608 (1983).

Parent, S., "POSIMETRIC Solids Injection Update," paper presented at the *2007 Gasification Technologies Conference (San Francisco, CA)*, Gasification Technologies Council, Arlington, VA (2007).

Perry, R. H. and Chilton, C. H. (Eds.), *Chemical Engineers' Handbook*, 5th Ed., McGraw-Hill, New York (1973).

Sprouse, K.M. and D.R. Matthews, "High Pressure Dry Coal Slurry Extrusion Pump," U.S. Patent Application No. 11/118,996 (2006).

Sprouse, K.M. and D.R. Matthews, "Linear Tractor Dry Coal Extrusion Pump," U.S. Patent Application No. 11/520,154 (2008).

Sprouse, K.M., D.R. Matthews, and G.F. Weber, "The PWR/DOE High-Pressure Ultra-Dense Phase Feed System and Rapid-Mix Multi-Element Injector for Gasification," paper 49-3 (Session 49) presented at the *23rd Annual International Pittsburgh Coal Conference*, University of Pittsburgh, PA (2006).

Sprouse, K.M., D.R. Matthews, and G.F. Weber, "PWR Dry Feed System Development for Compact Gasifiers," paper 25-1 (Session 25) presented at the *24th Annual International Pittsburgh Coal Conference*, University of Pittsburgh, PA (2007).

Sprouse, K.M., D.R. Matthews, and G.F. Weber, *Dry Coal Feed System and Multi-Element Injector Test Report*, Topical Report, DOE-NETL Cooperative Agreement DE-FC26-04NT42237 (Task 2: Injector and Feed System Development and Test), U.S. Department of Energy, National Energy Technology Laboratory, Pittsburgh, PA (2008).

Sprouse, K. M. and M. D. Schuman, "Dense-Phase Feeding of Pulverized Coal in Uniform Plug Flow," *AIChE Journal*, *29*, 1000 (1983).

Sprouse, K. M. and M. D. Schuman, "Dense-Phase Feeding of Pulverized Coal in Uniform Plug Flow," *AIChE Journal*, *32*, 1055 (1986).

Theuerkauf, J., S. V. Dhodapkar, and K. V. Jacob, "Modeling Granular Flow (Using Discrete Element Method -- From Theory to Practice)," *Chem. Eng.*, 39 (April 2007).

ACRONYMS AND ABBREVIATIONS

AI	Action Item
AIChE	American Institute of Chemical Engineers (New York, NY)
CA	California
CFD	Computational Fluid Dynamics
CoDR	Conceptual Design Review
DOE	Department of Energy
EERC	Energy and Environmental Research Center
FMEA	Failure Mode and Effects Analyses
GD	Granular Dynamics
GE	General Electric Corporation
HPDT	High Pressure Discharge Tank
IGCC	Integrated Gasification Combined Cycle
LPF	Linear Pocket Feeder
MN	Minnesota
MOC	Method of Characteristics
MTBM	Mean Time Between Maintenance
MTRR	Mean Time to Remove and Replace
MTSO	Mean Time for Shop Overhall
ND	North Dakota
NETL	National Energy Technology Laboratory
NTIS	National Technical Information Service
REACT	Rocketdyne Elliptic Analysis Code for Turbomachinery

PDR	Preliminary Design Review
PRB	Powder River Basin
PWR	Pratt & Whitney Rocketdyne
QA	Quality Assurance
RAM	Reliability, Availability and Maintainability
RSD	Relative Standard Deviation
UND	University of North Dakota
U.S.	United States of America