Achieve Continuous Injection of Solid Fuels into Advanced Combustion System Pressures

FINAL REPORT - PHASE II PROGRAM

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Abstract

The overall objective of this project is the development of a mechanical rotary-disk feeder, known as the Stamet Posimetric ® High Pressure Solids Feeder System, to feed dry granular coal continuously and controllably into pressurized environments of up to 35 kg/cm^2 (500 psi). This was to be accomplished in two phases.

The first task was to review materials handling experience in pressurized operations as it related to the target pressures for this project, and review existing coal preparation processes and specifications currently used in advanced combustion systems. Samples of existing fuel materials were obtained and tested to evaluate flow, sealing and friction properties. This provided input data for use in the design of the Stamet Feeders for the project, and ensured that the material specification used met the requirements of advanced combustion & gasification systems. Ultimately, Powder River Basin coal provided by the PSDF facility in Wilsonville, AL was used as the basis for the feeder design and test program.

Based on the material property information, a Phase 1 feeder system was designed and built to accomplish feeding the coal to an intermediate pressure up to 21 kg/cm^2 (300 psi) at feed rates of approximately 100 kilograms (220lbs) per hour. The pump & motor system was installed in a custom built test rig comprising an inlet vessel containing an active live-wall hopper mounted in a support frame, transition into the pump inlet, transition from pump outlet and a receiver vessel containing a receiver drum supported on weigh cells. All pressure containment on the rig was rated for the final pressure requirement of 35 kg/cm^2 (500psi).

A program of testing and modification was carried out in Stamet's facility in CA, culminating in successful feeding of coal into the Phase 1 target of 21 $kg/cm^{2\,(}$300psi) gas pressure in December 2003. Further testing was carried out at CQ Inc's facility in PA, providing longer run times and experience of handling and feeding the coal in winter conditions.

Based on the data developed through the testing of the Phase I unit, a Phase II system was designed for feeding coal into pressures of up to 35 kg/cm^2 (500 psi). A further program of testing and modification was then carried out in Stamet's facility, with the target pressure being achieved in January 2005. Repeated runs at pressure were achieved, and optimization of the machine resulted in power reductions of 60% from the first successful pressure runs.

General design layout of a commercial-scale unit was conducted, and preliminary cost estimates for a commercial unit obtained.

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Introduction

The overall goal of this project was to provide and confirm an alternative technological solution for solid fuel injection into proposed advanced combustion systems. Operators and designers of high-pressure combustion systems universally agree that one of the major problems inhibiting the success of this technology relates to solid materials handling at high pressures. Continuing problems feeding coal into high-pressure gas environments and the well-recognized complexity of existing handling systems has limited acceptance of advanced combustion and gasification technology. Limitations inherent in the batch process character of existing lock hopper and piston pump paste systems prevent controlled, continuous level delivery of the coal, imposing gas losses, high maintenance costs and substantial risks of downtime. This program is aimed at developing the Stamet Posimetric® High Pressure Solids Feeder to provide the simple, accurate and reliable feed system needed to maintain the lead of the U.S. in advanced combustion system design and supply.

The Posimetric® feeder has only one moving part, a rotating spool formed of two disks and a hub, which rotates within a stationary housing. Material entering the feeder becomes locked between the disks and is carried round as the spool rotates until it reaches the outlet port. This principle of lockup means the pump experiences virtually no wear. At the outlet a moving solids seal is continuously created, used as a seal and then dismantled as it is displaced by fresh material as the feeder operates into pressure. The solids pass through the feeder in a continuous unbroken stream, at a rate directly proportional to the speed of rotation.

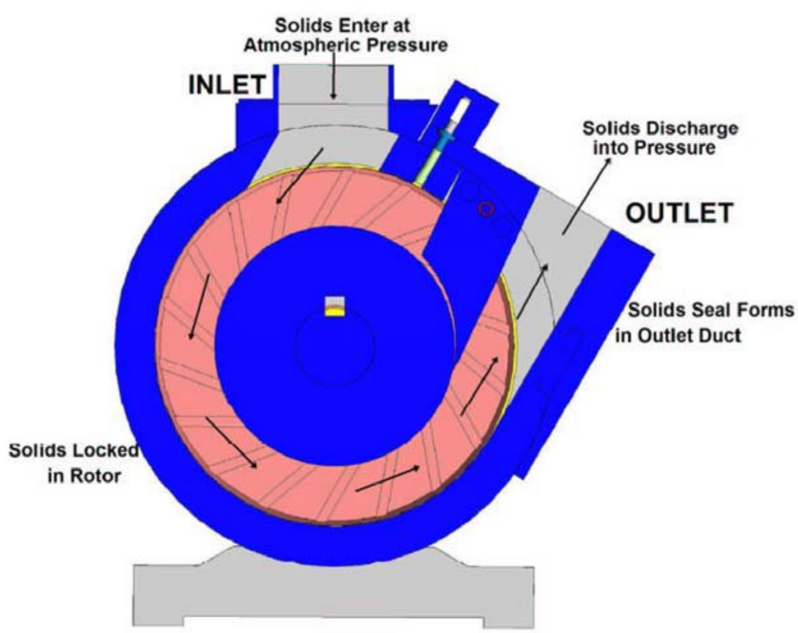

Fig. 1. Layout of Stamet Posimetric® Pressure Feeder

Previous work under SBIR grants has demonstrated the ability of the Stamet Posimetric ® High Pressure Solids Feeder to pump coal successfully into pressures as high as 11 kg/cm^2 (160 psi) and further development carried out by Stamet achieved successful pumping into 15 kg/cm^2 (210 psi). The plan for the current project provided for two phases extend this capability to achieve the final objective of feeding into35 kg/cm^2 (500 psi) as follows.

Phase 1:
Evaluate and select suitable coal material specification for feeder testing to minimize material handling issues affecting the program while maintaining relevance to the requirements of existing high pressure combustion and gasification processes.
Design, manufacture and test a semi-scale, 21 kg/cm^2 (300 psi) pressure capable, machine and test rig.
Test and evaluate design concepts and elements for internal pump configuration including inlet and outlet arrangements to build confidence in design for higher pressures in phase 2.

Phase 2:
Design, manufacture and testing of a modified feeder and test rig capable of discharging at the full operating pressure of 35 kg/cm^2 (500 psi).
Generate a general design and preliminary cost estimate for a commercial-scale feeder.

This report documents the work done on the project between October 2002 and April 2005, culminating in the successful feeding of coal into 35 kg/cm^2 (500 psi) and generation of a commercial-scale design.

Executive Summary

The overall objective of this project is the development of a mechanical rotary-disk feeder, known as the Stamet Posimetric ® High Pressure Solids Feeder System, to feed dry granular coal continuously and controllably into pressurized environments of up to 35 kg/cm^2 (500 psi).

The Posimetric® feeder has only one moving part, a rotating spool formed of two disks and a hub, which rotates within a stationary housing. Material entering the feeder becomes locked between the disks and is carried round as the spool rotates until it reaches the outlet port. This principle of lockup means the pump experiences virtually no wear. At the outlet a moving solids seal is continuously created and then dismantled as it is displaced by fresh material as the feeder operates into pressure. The solids pass through the feeder in a continuous unbroken stream, at a rate directly proportional to the speed of rotation.

The program was to be accomplished in two phases as follows:

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Evaluate and select suitable coal material specification for feeder testing to minimize material handling issues affecting the program while maintaining relevance to the requirements of existing high pressure combustion and gasification processes.
Design, manufacture and test a semi-scale, 21 kg/cm^2 (300 psi) pressure capable, machine and test rig.
Test and evaluate design concepts and elements for internal pump configuration including inlet and outlet arrangements to build confidence in design for higher pressures in phase 2.

Phase 2:
Design, manufacture and testing of a modified feeder and test rig capable of discharging at the full operating pressure of 35 kg/cm^2 (500 psi).
Generate a general design and preliminary cost estimate for a commercial-scale feeder.

The first task was to review materials handling experience in pressurized operations as it related to the target pressures for this project, and review existing coal preparation processes and specifications currently used in advanced combustion systems. Samples of existing fuel materials were obtained and tested to evaluate flow, sealing and friction properties. This provided input data for use in the design of the Stamet Feeders for the project, and ensured that the material specification used met the requirements of advanced combustion & gasification systems. Ultimately, Powder River Basin coal provided by the PSDF facility in Wilsonville, AL was used as the basis for the feeder design and test program.

Based on the material property information, a Phase 1 feeder system was designed and built to accomplish feeding the coal to an intermediate pressure up to 21 kg/cm^2 (300 psi) at feed rates of approximately 100 kilograms (220lbs) per hour. The pump was designed and built as small as possible consistent with retaining inlet flow capability to minimize the cost of the initial machine and subsequent modifications. The pump & motor system was installed in a custom built test rig

comprising an inlet vessel containing an active live-wall hopper mounted in a support frame, a transition into the pump inlet, a transition from pump outlet and a receiver vessel containing a receiver drum supported on weigh cells. All pressure containment on the rig was rated for the final pressure requirement of 35 kg/cm^2 (500psi). The inlet hopper of the pump was contained in a pressure vessel so that during testing to investigate any failure modes, the material and gas would be contained within the rig. The system was fully instrumented and controlled from a PC using custom LabVIEW programming.

A program of testing and modification was carried out in Stamet's facility in CA, feeding coal into progressively increasing pressure, culminating in successful feeding of coal into the Phase 1 target of 21 $kg/cm^{2\,(}$300psi) gas pressure in December 2003. Following this the complete rig was shipped to Homer City, PA where further testing was carried out at CQ Inc's facility, providing for longer run times and giving experience handling and feeding the coal in winter conditions.

Based on the data developed through the testing of the Phase I unit, a Phase II system was designed for feeding coal into the final target pressures of up to 35 kg/cm^2 (500 psi). A further program of testing and modification was then carried out in Stamet's facility, with the target pressure being achieved in January 2005. Repeated runs at pressure were achieved, and further optimization of the machine design resulted in power reductions of 60% from the first successful pressure runs.

This demonstrated the feasibility of using the Stamet Posimetric® High Pressure Solids Feeder System up to the required pressures and provided data on power and sizing requirements for commercial applications. The general design layout of a commercial-scale unit was conducted, and preliminary cost estimates for manufacture of a commercial scale unit obtained.

Experimental.

Material Evaluations:

The project commenced with review of current equipment and operating specifications of pressurized combustion and gasification systems and identification of feed material properties desirable for achieving the target pressures. Additionally, coal preparation processes were reviewed to develop a proposed material specification that ensured final feed material specifications were consistent with coal preparation plant capabilities and advanced combustion systems being fed. Samples were obtained from users for evaluation.

Samples were subjected to a sieve analysis and moisture measurement. They were additionally evaluated for properties that would be important to the operation of the pump including flowability, bulk density, compressibility, friction and permeability.

Inlet flow characteristics were evaluated by measuring flowrates through a series of hoppers with different sized exits. Hoppers were filled via a small conveyor to ensure consistent fill rates, and then the outlet was opened and the time for the hopper to empty measured.

Fig.2 Filling Test Hopper

Fig.3 Emptying Test Hopper.

Bulk density, compressibility friction and permeability were evaluated using a custom designed STA-meter to measure the **S**olids **T**ransport **A**ttributes of the materials. In this device a known weight of material is added into a tube to provide a column of material. Gas pressure can be applied to the top of the column, which can then be driven up the tube by a piston from below. Measurements of column length, friction force, pressure and gas leakage rates allow density, compressibility, friction and permeability of different samples to be evaluated.

Fig.3 STA-meter

Test Pump:

The research program was designed to minimize the cost to achieve the target pressure level. Rather than building two complete machines for phase 1 & 2, the phase 1 unit was designed to allow it to be modified to meet the Phase 2 requirements.

Fig.4 Spool Assembly

Fig.5 Pump Body

As with all Posimetric® feeders, the research pump has only one moving part – the spool (Figure 3). , comprising two discs and a hub spacer on a shaft. The spool rotates inside the body housing (Figure 4). Unique to this body design was the use of inserts for inlet and outlet components. These allow the inlet and outlet configurations to be readily changed without requiring major modifications to the pump body.

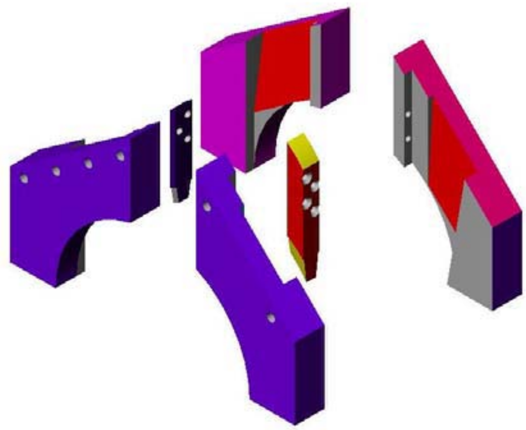

Fig. 6 Inlet & Outlet Inserts

Pump Test Rig:

The pump was mounted on a platform and coupled to an electric motor/gearbox unit via a drive chain. The electric motor was powered via a variable frequency drive to provide speed control from 0 to 5 rpm.

The pump & motor system was installed in a custom built test rig comprising an inlet vessel containing an active live-wall hopper mounted in a support frame, a transition into the pump inlet, a transition from pump outlet and a receiver vessel containing a receiver drum supported on weigh cells.

The rig was instrumented to monitor pressures throughout the system, material presence and flowrates, gas flowrates, speed and drive torque. The system was controlled from a PC using custom LabVIEW programming which also recorded the sensor data in real time. Video recordings were also made during testing showing the outlet feed condition, inlet flow and data capture screen.

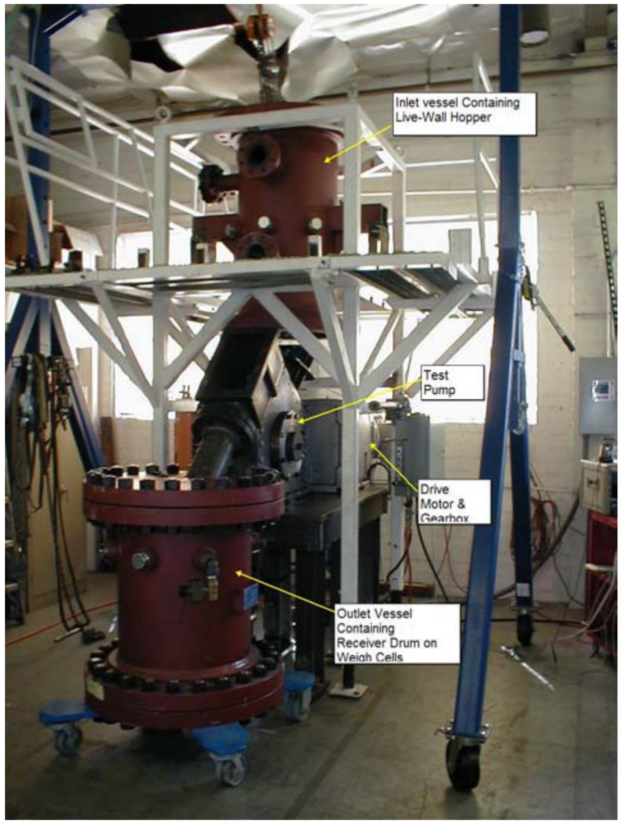

Fig.7 Pump Test Rig

All pressure containment on the rig was rated for the final pressure requirement of 35 kg/cm^2 (500psi). The inlet hopper of the pump was contained in a pressure vessel so that during testing to investigate any failure modes the material and gas could be contained within the rig. The system was fully instrumented and controlled from a PC using LabVIEW programming.

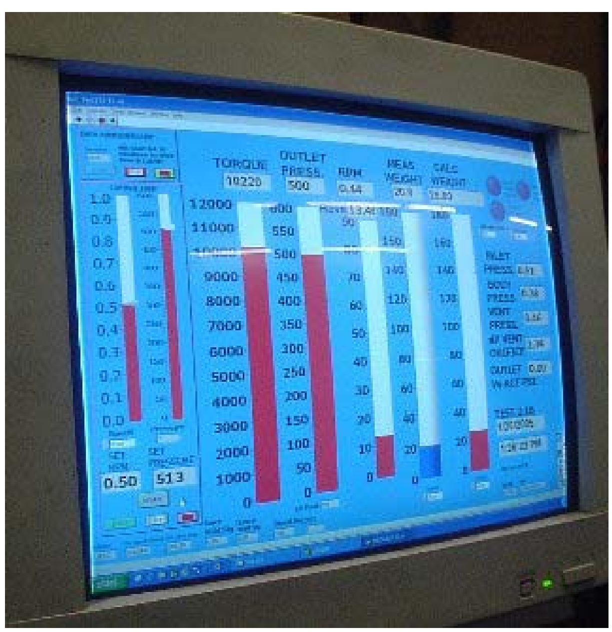

Fig.8 Dataq & Control Screen

Results and Discussion.

Material Evaluations:

Samples of existing fuel materials were obtained and tested to evaluate flow, sealing and friction properties. This provided input data for use in the design of the Stamet Feeders for the project, and ensured that the material specification used met the requirements of advanced combustion & gasification systems. Typical data obtained is shown below.

STAMET HOPPER TESTING

DATE 2/26/2003

RUN NO. 03022601

TEST COAL

Source: Wilsonville PRB Coal (as-received)

Type/Topsize: Sub-Bituminous Coal, Very Fine

Moisture (Wt%): TBD (~ 26-30)

HOPPER:	A	B	C	D
Discharge (mm x mm)	76 x 38	65 x 32.5	52 x 26	40 x 20
Time to Empty (secs)	11.38	16.78	28.73	55.80
Observations	Free Flowing the entire period. Flow was more "funnel" like than mass-flow (I.e., material drawn down quicker from the center, slightly slower along the sides). Coal is very fine, and dusty while loading and discharging.	Same	Same	Same
Coal Weight (grams):	9,815	9,815	9,815	9,815
Flowrate, gm/s	862.4780316	584.9225268	341.6289593	175.8960573
Flowrate, lb/s	1.901438906	1.289533656	0.753163061	0.387784494
Density, lb/cu.ft	45	45	45	45
Flowrate, cu.ft/s	0.042254198	0.028656303	0.016736957	0.008617433
Flow Area, sq.mm	2888	2112.5	1352	800
Flow Area, sq.ft	0.031086173	0.022738761	0.014552807	0.008611128
Velocity, ft/s	1.359260193	1.260240335	1.150084451	1.000732176
ft/min	81.55561159	75.61442008	69.00506705	60.04393054

STA-METER TESTING

DATE 2/26/2003

RUN NO. 03022602 (repeat of Run 03022101)

TEST COAL

Source: Wilsonville PRB Sub-bit Coal

Type/Topsize: As-received (8M topsize)

Moisture: 21.08 *wt%*

Initial Wgt.: 230.9 *grams*

Remaining Wgt.: 198.3 *grams*

Sample Wgt.: 32.6 *grams*

TEST MEASUREMENTS

Initial Column Hgt.: 140 *mm*

Final Column Hgt.: 130 *mm*

Initial Leakage: 22 *scfh*

Final Leakage: 21 *scfh*

Hydraulic Pressure: 140 *psi* **(max)**

OBSERVATIONS

Hydraulic pressure varied with stroke, typically in 110-140 psi range. Max pressure was 140 psi. After test, most of the material was easliy poured out from top of sample tube with only light tapping; the remainder poured out from the bottom as the push rod was withdrawn.

Fig.9 Material Test Data

Analysis of the data collected showed the Wilsonville PRB samples to provide excellent input flow properties, so that reliable inlet flow would be obtained. The friction loads were somewhat higher than other samples, but there was little variation in sealing capability. Discussions with site personnel visited had indicated that future requirements of their processes may lead to somewhat finer material being used, but little other modifications to the material specifications. Testing indicated that this would only lead to a reduction in venting requirements for the Stamet feeder which would be accommodated by designing for higher flow. The decision was made to proceed using the determined properties of the coal provided by Wilsonville PSDF as the basis for the feeder design, resulting in a feeder designed to handle the higher friction and flow requirements tested, so providing some flexibility in future fuel specifications, and allowing the use of a commercially available fuel for the project.

Phase 1 Testing:

The original pump configuration had been selected to maximize the drive capability by maximizing the angle between inlet and outlet to create the longest effective length of the duct, and minimize the resistance to flow by providing clear inlet and outlet paths. Initial checks were first carried out to confirm the basic functionality of the pump mechanicals and operation of the control and data acquisition systems. All systems operated successfully and initial data was obtained on the basic torque characteristics of the pump as originally configured, both empty and feeding coal into atmospheric pressure at a range of speeds.

The inlet flow system incorporated a patented live wall hopper system, which was actuated by void sensors at the pump inlet. Visual observations in the inlet when feeding the Wilsonville coal showed a tendency for the coal to rat-hole at the front side of the hopper, but once a void reached the sensors the vibrators actuated briefly and the rat-hole collapsed. Due to the rat-holing tendency of the coal being used the control system was subsequently modified to include the option of a timed actuation of the vibrators to help ensure consistent inlet flow, which is critical to the correct operation of the system.

With the original, strongly diverging outlet configuration of the pump very little additional resistance was observed when feeding Wilsonville coal into atmospheric conditions. The torque levels increased due to the coal friction on the glide and through the outlet, and showed a similar dependency on speed, but the difference was only about 70Nm (50 ft.lbs.) To confirm adequate duct filling and drive in the pump, a mechanical load was then applied using an air-spring loaded plate to resist the coal flow at the pump exit.

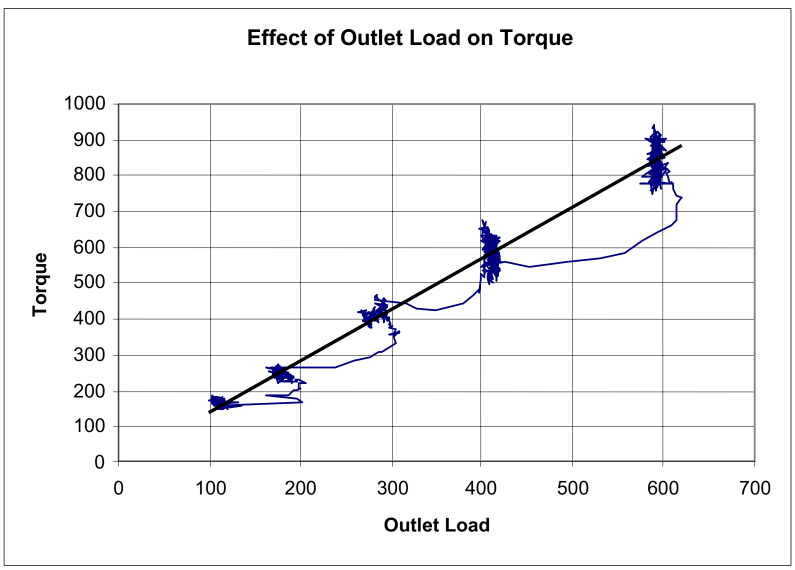

Fig.10 Relationship of Torque vs Outlet Load

Fig.10 shows typical data obtained, showing a linear increase in drive torque as outlet load was applied, indicating that a good grip was being obtained on the material in the pump duct. Steady outlet flow was obtained over the course of the tests confirming the ability to drive material in a controlled manner against a resistance.

Initial trials were then carried out feeding the Wilsonville coal into gas pressure, and Fig. 11 shows typical results obtained from the original configuration.

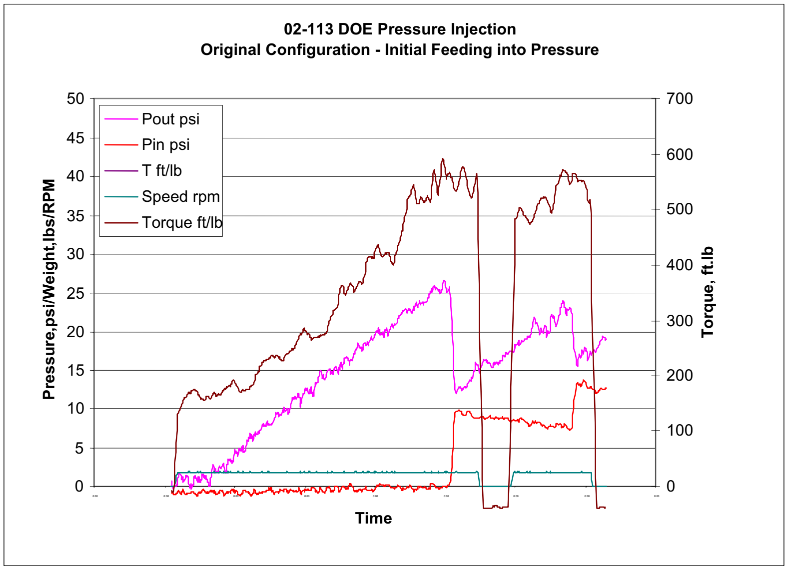

Fig.11 Original Gas Testing Data

As gas pressure is applied to the outlet of the running pump the drive torque increases with it. However, in this case at 1.75kg/cm^2 (25psi) outlet pressure the outlet seal is suddenly lost and the gas pressure drops. When the pump is stopped and restarted the same thing recurs. With this outlet configuration a stable seal was not obtained with the Wilsonville coal, and eventually a rat-hole occurred in the outlet allowing gas to flow back through the pump. Changes to the outlet geometry were needed to establish a stable seal and allow reliable operation at higher outlet pressures.

The outlet inserts were modified to provide a much greater resistance to the outlet flow of material in order to establish a consolidated, stable material seal in the outlet. At the same time changes were incorporated to address issues with the disk sealing system, which had shown some binding and distortion during the course of the testing. This arrangement resulted in a stable outlet plug but required excessive torque when outlet pressure was applied.. Subsequent changes were made to the outlet inserts to progressively reduce the restrictions to flow so that a balance could be obtained where sufficient resistance was applied to produce a stable gas seal without exceeding the drive capability of the system.

After several iterations a balanced geometry was reached which provided a stable outlet gas seal without locking the rotor at full load. With this geometry the first run to feed coal into 21 kg/cm^2 (300 psi) was made in late December 2003. Data from this run is shown in Fig.12.

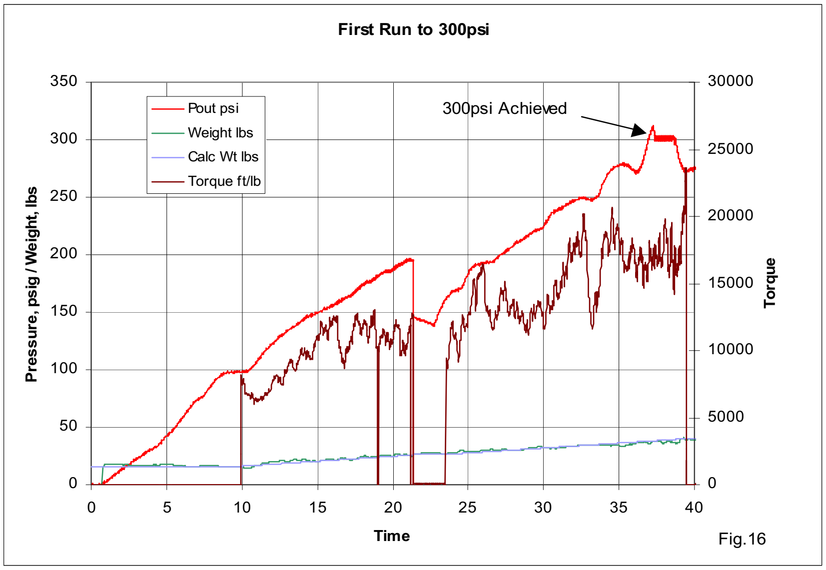

Fig.12 First Successful Run to 21 kg/cm^2 (300psi).

This outlet geometry still resulted in considerable resistance to the flow, requiring substantial torque to drive the material into the outlet containment. However, despite the high torque requirement the weight pumped was in good agreement with the calculated value, confirming that as long as the pump inlet is kept consistently filled with material the throughput remains directly proportional to rotational speed.

Fig.13 shows the relationship between the torque requirement and the outlet pressure. Although there are fluctuations due to variations in the material, the trend-line on the graph clearly illustrates a linear relationship between the two variables, and also confirms the considerable grip and drive available from this pump configuration.

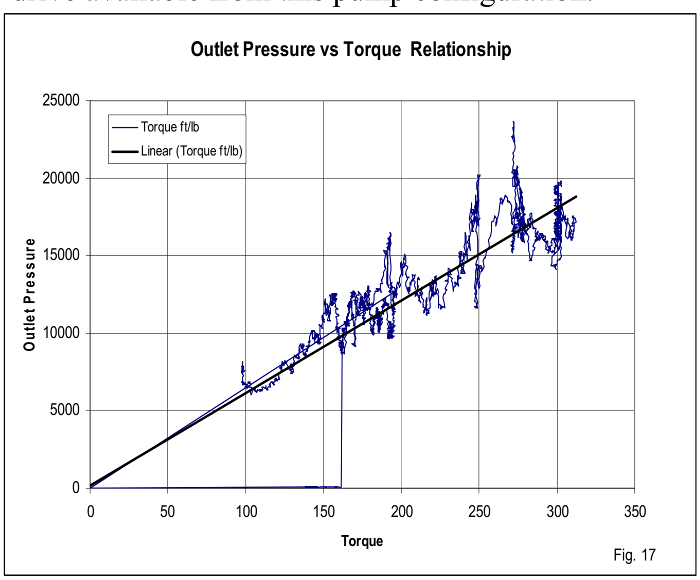

Fig.13 Relationship of Torque to Outlet Pressure.

After achieving the target of pumping into 21 kg/cm^2 (300 psi) pressure, the test rig was transported to CQ Incorporated's larger facility in Homer City, PA. The equipment was installed and checked out in January 2004, and further extended test runs were made through the end of February 2004 to evaluate coal handling in winter conditions and test further outlet changes. Through the series of runs the torque requirement for the different geometries was monitored and some reduction was obtained. This is illustrated in Fig. 14, which shows the torque trend-lines for the first, last and an intermediate run illustrating the drop in torque requirement.

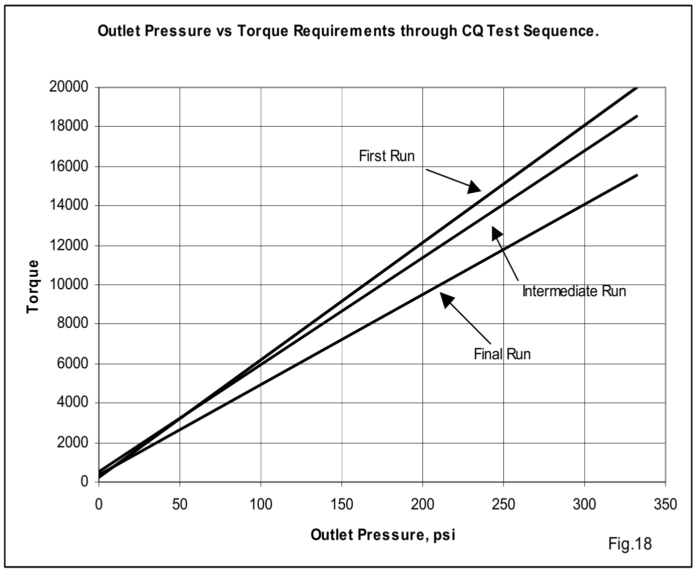

Fig.14 Torque Reductions Obtained in Phase 1.

Phase 2 Testing:

With a target of feeding coal into a gas pressure of 35 kg/cm^2 (500psi), the second phase focused on optimization, particularly in the outlet configuration, to reduce power requirements and loads in the pump. Instrumentation and monitoring equipment was also upgraded to provide more detailed data.

Modifications were made to the pump to allow visual monitoring of pump internals during operation by the use of clear polycarbonate components. While pressure capability in this mode was limited it provided better understanding of the mechanics of operation and flow regimes in the pump outlet. This knowledge was used to design and subsequently modify outlet inserts to achieve more optimal flow.

Fig.15 Flow Visualization Testing with Plastic pellets.

From this input the research team developed a number of modifications, particularly in the outlet area, that significantly reduced torque requirements. This area was the focus of considerable design and testing during this part of the program as visual flow tests indicated the majority of torque was being consumed in this region. Considerable testing was done to evaluate the flow in this region and develop geometry to optimize the flow.

A 3D outlet was manufactured in a reinforced nylon material by stereolithography. This enabled a complex optimized configuration in the transition from disc containment to outlet duct to be manufactured quickly and accurately directly from a computer generated solid model. This component was used for visual flow testing and then actual pumping with coal. This nylon duct worked so well that it was used for pressure tests. During testing the outlet was progressively shortened to determine effect on torque requirements and sealing capability. The result of this optimization process was that torque for a given pressure was reduced by 50-60 percent over the outlet configuration used for the phase 1 tests while still maintaining a stable seal. The 35kg/cm^2 (500psi) pressure target was first achieved in January 2005 using this nylon outlet insert. Data from that test run is shown in Fig.15.

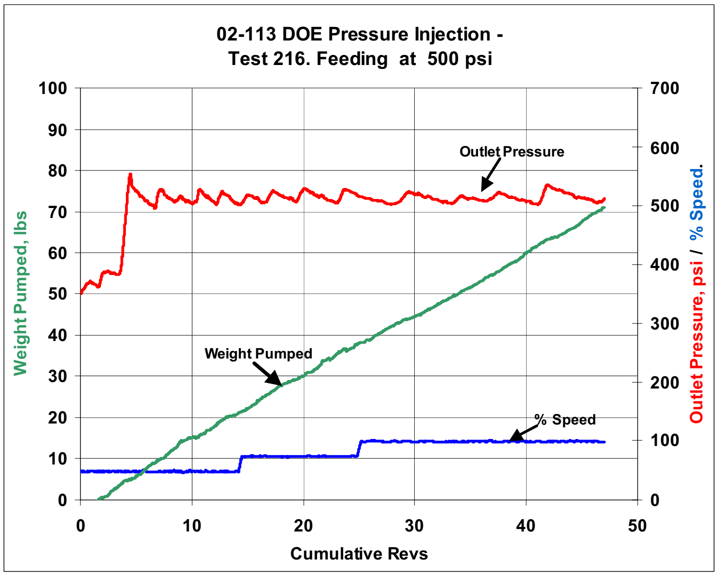

Fig.15 First Successful Run to 35 kg/cm^2 (500psi

The Stamet Posimetric® feeder was subsequently operated repeatedly for durations exceeding two hours feeding into gas pressures at and above 35 kg/cm^2 (500psi). These runs also confirmed the ability of the pump to stop & start under pressure while retaining a stable gas seal.

The overall torque reductions achieved from the beginning of the program to the end – over 50 percent - is shown in Figure 16. illustrating the major improvement in efficiency achieved during Phase 2.

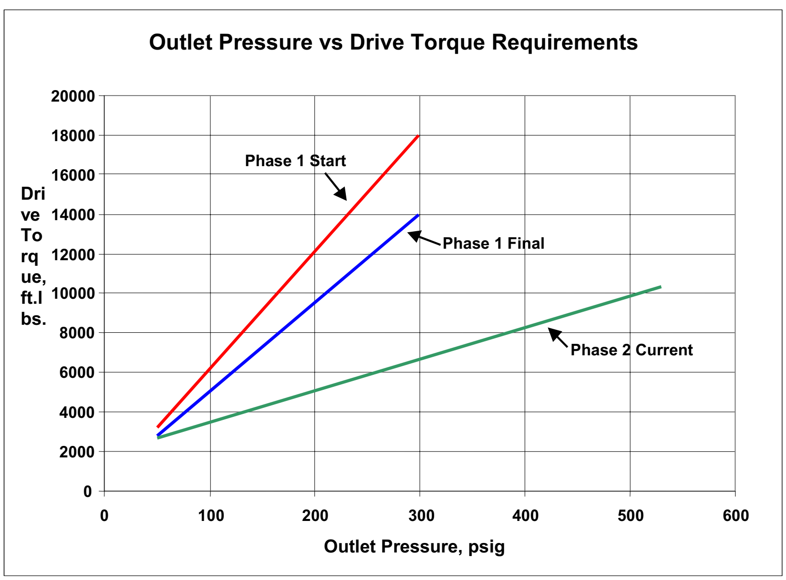

Fig.16 Torque Reductions Achieved.

Also of particular significance to practical applications, the operation of the feeder at these pressures saw very low requirements for make-up gas as shown in Figure 12. Typical make-up gas requirements were less than 5×10^{-4} m^3/s. This would scale up in a commercial sized feeder, but level of flow still offers the significant benefit to gasifier operations of greatly reduced gas consumption over lock-hopper systems.

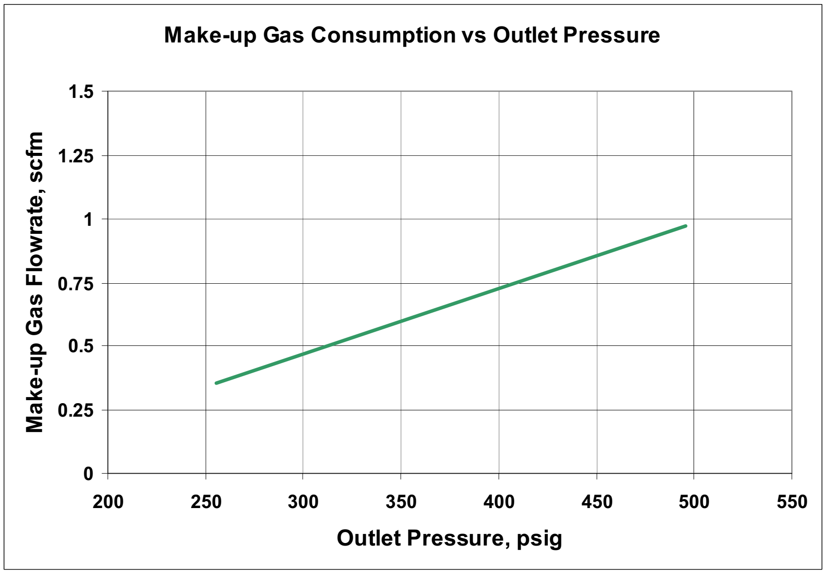

Fig.17 Make-up Gas Requirements

The phase 2 work successfully demonstrated the use of the Stamet Posimetric® High Pressure Solids Feeder System for feeding into gas pressures in excess of the 35 kg/cm^2 (500psi) target.

Commercial Scale Feeder Estimates

A deliverable for the program is a general design and cost estimate for a commercial scale high-pressure feeder. Stamet has studied the results of the test program and in conjunction with industry gasification operators developed the expected configuration for a commercial feeder.

One major benefit of the Stamet Posimetric® feeder concept is its modularity, allowing multiple disc's to be assembled on a common shaft, in essence a series of feeders in parallel. This allows feed capacity to be increased in uniform increments and potentially has no upper limit other than practical machine size. The proposed commercial design is based on the multiple disc concept with the machine sized for expected gasifier feed requirements of 25 TPH, which is considered a nominal stepping-stone and building block for commercial systems.

Fig. 18 shows the conceptual feeder design layout for a commercial application, including inlet feed hopper and outlet transition.

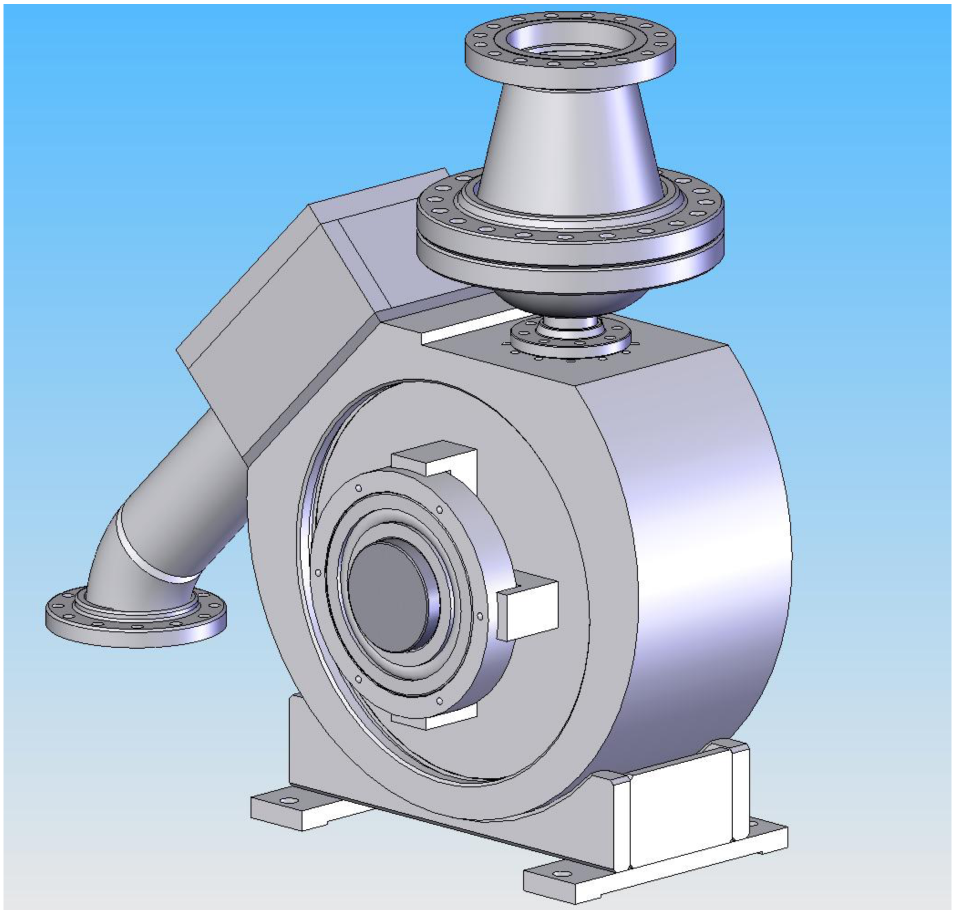

Fig. 18. Commercial Feeder Layout

Estimated specifications for a 25 TPH feeder are as follows:

Feed rate for pre-pulverized PRB, Bituminous or Lignite fuel	25TPH
Fuel Size	90% -200#
Fuel Moisture Content	2-5%
Disc diameter:	1.5m
Number of Discs:	3
Pressure capability:	35 kg/cm^2 (500psi)
Feeder footprint:	
Feeder Height:	2m
Feeder Width:	1m
Feeder Weight:	10t
Motor Power:	200kW
Feeder Cost of Manufacture	$350,000

Other components that will be required as part of a feeder system will include inlet transition live-wall hopper, inlet transition pressure vessel, inlet isolating valve, outlet isolating valve and PLC control system. Cost for these components is estimated at $50,000.

Conclusions.

The program successfully demonstrated the ability of the Stamet Posimetric® High Pressure Solids Feeder System to feed dry granular coal into pressures exceeding the 35 kg/cm^2 (500psi) target.

The pump was able to stop & start under load while retaining a stable gas seal.

The requirements for make-up gas were very small compared with usage in existing lock-hopper systems.

A general design and preliminary cost estimate for a commercial-scale feeder capable of 25tph into 35 kg/cm^2 (500psi) of pressure was generated, indicating unit costs of the order of $350,000.