Proof of Principal Test to Feed and Meter Granular Coal into 450 psig Gas Pressure.

Final Report

Prepared by : Derek L. Aldred,

Issued: July 2000.

Project # DE-FG26-98FT40330

STAMET INC.,
17244 South Main Street,
Gardena, CA 90248-3130

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Abstract

This research program is concerned with the development of a new form of feeder, known as the Stamet Posimetric ® High Pressure Solids Feeder, to feed dry granular solids continuously and controllably into gas pressure. The device is a rotary mechanical feeder, which utilizes the interlocking and internal friction of the granular solids to drive the solids through into the outlet pressure in a continuous and controllable way, using a continuous solids material seal on the feeder outlet to control gas leakage.

Earlier work sponsored under previous SBIR grants has successfully demonstrated the potential benefits of the Stamet machine over pressurized lock hopper or paste feeder methods. The objective of this project was to demonstrate proof of principal to feed and meter specified granular coal into 450 psig gas pressure for use with next generation pressurized fluidized bed combustors.

This report encompasses the development of material transport properties testers, methods to predict feeder performance by calculation, and the modification and testing of Stamet feeders to feed the material supplied into pressure.

Testers were made to measure material compressibility, bulk density, both internal and wall friction coefficients, and permeability under typical conditions experienced inside a Stamet high pressure feeder. This data is then used in support of ongoing efforts to develop calculations to predict the performance of Stamet pressure feeders with different materials and conditions.

Three Stamet pressure feeders were modified to handle the fine granular or pulverized coal, and were tested under various conditions using different outlet arrangements. The initial testing identified difficulties in handling the fine materials, but through a series of calculations and tests, the issues were overcome and the material was successfully fed into pressure.

In all cases the performance calculated based on the measured material properties and feeder geometry agreed well with the test results, confirming the ability to predict performance and select geometry required to handle different conditions. However, the maximum pressure achieved was limited by an ineffective auger design, which was unable to effectively control the length of the outlet seal at higher pressures without imposing additional mechanical loads on the surface of the coal seal. This prevented steady state conditions being maintained long enough to reach the target pressure.

Though the specified coal was successfully pumped into pressures over 200 psi, and the test results clearly indicate the changes required to provide a fixed outlet geometry that would achieve the 450 psi target, time and funding was not available to pursue this goal further under this project.

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Introduction

This research program, conducted by Stamet Incorporated, is concerned with the development of a new form of feeder known as the Stamet Posimetric ® High Pressure Solids Feeder, to feed dry granular solids continuously and controllably into gas pressure. The device is a rotary mechanical feeder that utilizes the interlocking and internal friction of the granular solids to drive the solids through the feeder duct into the outlet gas pressure in a continuous, controlled stream. (see Fig. 1)

The 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. 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.

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 160 psig and further development carried out by Stamet achieved successful pumping into 210 psi. The specific objective of this project is to demonstrate proof of principal to feed and meter specified fine granular coal into 450 psig of gas pressure for use with the next generation of pressurized fluidized bed combustors.

The earlier high pressure work had been carried out using blended coals that allowed for some optimization of the containment and sealing characteristics of the material, thus allowing more rapid progress to be made in confirming the necessary design parameters for high pressure machines. The program reported here was to use much finer granulated or pulverized coals, so the requirements to handle these fine ground materials had to be established, and Stamet feeders and test rigs provided to feed the material under test at the higher pressure levels.

The Stamet feeders and test rigs that had been developed through the earlier research programs were available as possible test vehicles for this program. However, the test rigs were only rated for 250 psig, so required upgrading for use up to the target pressure of 450 psig. Also, the basic design parameters of one of the existing Stamet feeders indicated that it should be capable of reaching the target pressure for this program. This meant that the basic hardware needed in support of this program was available, requiring only modification to handle the fine coal, and development of an adequate outlet solids seal geometry to withstand the target pressure.

In support of this, additional experimental evaluation of materials properties was necessary to provide data to assist in the correlation of experimental data with anticipated performance of the test feeders. Calculation methods were therefore needed to apply this data to predict Stamet feeder performance with different materials, and to develop design optimization capabilities for future applications.

The program for this project therefore provided for initial materials testing and the development of performance calculation methods to use this data to predict pump performance. Evaluation of the outlet geometry required to create an effective and stable solids material seal with the specified material was a major component in this effort. This would be followed by the required hardware pressure upgrades, and the necessary machine modifications required to contain and feed the fine materials. A series of evaluation tests using the available Stamet feeders at progressively increasing pressures was then planned to confirm the various assumptions used and predictions made, progressing toward the final target of pumping into 450 psig.

Executive Summary

This research program conducted by Stamet Incorporated, is concerned with the development of a new form of feeder, known as the Stamet Posimetric ® High Pressure Solids Feeder, to feed dry granular solids continuously and controllably into gas pressure. The device is a rotary mechanical feeder that utilizes the interlocking and internal friction of the granular solids to drive the solids through the feeder duct into the outlet pressure in a continuous, controlled stream. The objective of this project is to demonstrate proof of principal to feed and meter specified granular coal into 450 psig of gas pressure for use with the next generation of pressurized fluidized bed combustors.

Previous work under SBIR grants had demonstrated the ability of the Stamet feeder to pump successfully into pressure, so machines and test rigs were available, though they required modification to meet the needs of this project. The earlier high pressure work was carried out using blended coals to allow optimization of the containment and sealing characteristics of the material to enable more rapid progress to be made in confirming the necessary design parameters for high pressure machines. This program was to use much finer granulated or pulverized coals, so the requirements to handle these fine ground materials had to be established.

Initial evaluation runs using coal supplied from the Wilsonville test facility were carried out using an existing high pressure feeder. This disclosed several problems in handling very fine materials with the existing feeders, and it was clear that improved sealing and gas venting systems would be required. It was also apparent that the properties of the material being fed had a significant bearing on the design parameters necessary for successful feeding, indicating a need to further develop calculation methods to predict feeder performance and geometry requirements by evaluation of materials properties and application conditions.

Test rigs were designed and built to measure important materials characteristics and properties relevant to their performance in a Stamet High Pressure Feeder. This data was then used in calculations developed to predict feeder performance and allow design parameters to be optimized for particular applications.

Preliminary testing was carried out on a small feeder using pulverized coal to confirm the effectiveness of the sealing and venting modifications proposed for the larger feeders. Both sealing and venting arrangements worked well up to the 50psi operating limit for this feeder rig. Sealing characteristics of the solids material outlet plug and the HP required to drive the feeder were compared with predictions calculated from the measured materials data and feeder geometry. Measured leakage rates correlated well with calculated values, whilst the measured HP was somewhat lower than predicted.. This was explained by the inability of the small scale test rig to maintain a steady state test condition since testing was carried out with a continually increasing outlet seal length so that the load always lagged behind the level it would have been at steady state conditions. These test results also confirmed that, as calculated, the power draw increases

exponentially with the length of the outlet seal, while the gas leakage rate decreases. Therefore, in a given situation, a compromise can be selected to minimize the power requirement while still containing gas leakage rates to acceptable levels.

A larger feeder, designed for 250 psig and designated as the 0230, was then modified to incorporate the seal and venting arrangements proven out on the small high pressure feeder and was installed into a test rig that allowed steady state conditions to be maintained while pumping. This required the selection of fixed outlet geometry for use with the pulverized coal at up to 200 psi. This geometry was selected based on the predictive calculations described to compromise between leakage control and required HP. In this instance, the choice of outlet geometry was also constrained to be at least as large as the outlet from the integral divergent in the feeder outlet, though for the pulverized coal used in these tests a compromise of sufficient diameter was found .

A series of tests was then carried out on this feeder configuration, and the data obtained compared with the performance predictions. This series of tests successfully contained the pulverized coal and pumped it into 180 psi within the available HP and with minimal controlled leakage. The performance predictions had successfully defined geometry to allow pumping of the selected coal into pressure, and the data obtained again correlated well with the performance predictions for the material and geometry used.

The final testing program was then carried out on a high pressure feeder, termed the SBIR feeder, which was rated for 450 psig and had a smaller outlet than the 0230 feeder. As before, this feeder was modified to incorporate seals and gas venting. The testing with the fine granular coal supplied from Wilsonville showed it to have much poorer sealing characteristics than the pulverized coal, so a smaller cross-section outlet configuration was required. A square section tube was selected as being the smallest section that would mate with the feeder outlet to minimize leakage. The tube was left as long as could be accommodated in the test rig. Although this was longer than the optimum length indicated by calculation, it would allow an extended range of testing to be carried out. To enable different lengths to be tested without major rig revisions being required, an auger was installed inside this pipe to break up the outlet column at any desired length shorter than the maximum,

These tests successfully created a stable seal with the Wilsonville coal, and the results were again in agreement with predictions. Unfortunately, it was found that at higher gas pressures the auger was unable to break up the outlet column without imposing additional mechanical loads on the coal surface so steady state conditions could not be maintained. This allowed only short duration tests, which prevented the full pressure being reached. However, the data obtained did confirm the calculation that an intermediate length of the square duct would provide a satisfactory seal and allow feeding into 450 psig.

At this point time and funds for the project were exhausted, so further testing will need to be done as part of a future project.

Experimental

Initial Evaluation

Previous work under SBIR grants has demonstrated the ability of the Stamet High Pressure Feeder to pump coal continuously into pressures as high as 210 psi. The Stamet High Pressure Feeder developed for this testing program was designated the SBIR high pressure feeder, and will be referred to as such throughout this report. In addition to this feeder, two other pressure feeders were available within Stamet and were used for various tests as will be described. All units followed the same basic methods of operation and construction, as described here with reference to the SBIR feeder shown in Fig 1.

The feeder has only one moving part, a rotating spool, which rotates within a stationary housing. In the units tested here, this spool is formed of two disks mounted on an industrial reduction torque hub which provides the final slow speed drive to the spool. The hub and housing are mounted concentrically on a back-plate to maintain the necessary location and accuracy. Material enters the feeder under gravity through the inlet on the top of the machine. This guides the material into the annular drive duct, three textured sides of which are formed by the rotating spool, with the fourth being the smooth, stationary outer wall provided by the housing. The material becomes locked between the textured faces of the moving disks and is carried round through the drive zone as the spool rotates until it reaches the disengagement zone at the outlet port. There the material is guided out of the duct by an abutment, which protrudes into the duct and releases the material from the moving duct walls. The material then passes into the outlet duct, where 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. At the end of the outlet duct the material is released into a tee and then allowed to fall under gravity into a receiver vessel as shown in Fig. 2. The solids pass through the feeder in a continuous unbroken stream, at a rate directly proportional to the speed of rotation.

The SBIR unit incorporated a 32" diameter drive duct mounted on a commercial torque hub drive, contained within a fabricated body and outlet duct. The unit was hydraulically driven and was mounted in a high pressure test rig as shown in Fig 2. This comprised

- a Stamet designed vibratory hopper and feed mechanism above the feeder providing a gravity feed to the feeder inlet.
- the Stamet feeder discharging upwards through piping, and then downwards by gravity into a pressure vessel.
- a pressure vessel which could be pressurized from an external gas supply and contained a weigh-cell system to allow the discharge material to be continually weighed under pressure.
- a data acquisition system supplemented by additional gauges allowing continual recording of the feeder rotation, material output, gas pressure and power draw.

This arrangement allows the system to be run in a batch mode, wherebye a hopper of material can be transferred into the pressure vessel during a monitored run. The system must then be shut down and de-pressurized so that the pressure vessel can be opened and emptied before the next run can commence. (A more detailed description of the machine and test rig can be found in the reports from the earlier SBIR grant program.)

This high pressure test rig had originally been designed to operate at pressures up to 250psi so the modifications required to increase the pressure containment capability to 450 psig were identified and the components required selected, purchased and installed.

The earlier high pressure tests had been carried out using blended coals, generally at least ¼"- or ½"- with added fines, which had been selected to somewhat optimize the containment and sealing characteristics of the material. In these tests material was successfully pumped, although considerable material spillage and gas leakage was experienced from the machine. The testing had also demonstrated the sensitivity of the system to the properties of the material being pumped, and the need for a method to optimize the feeder and outlet geometry to handle particular material characteristics.

Subsequent to this work on the SBIR feeder, which had confirmed some basic design parameters for the machines, a later design of feeder was built designated the 0230. This unit, with a 30 in. diameter duct, used a similar torque hub drive system as the SBIR unit, and combined a fabricated body with a one-piece cast outlet divergent duct. (see Fig.3) This design was felt to be a step closer to a commercial machine design than was the original SBIR concept. This machine could be installed in the same test rig as the SBIR feeder and so was also available to run evaluation tests within Stamet.

The first tests carried out using fine granular coal supplied from the Wilsonville test site used the 0230 feeder installed in the high pressure test rig as described above. As described in detail later, these tests disclosed considerable problems in handling the material with the existing feeders. The fine coal exposed the poor sealing characteristics of the existing designs, and considerable coal and gas leakage was experienced from the feeder. Clearly these existing designs did not incorporate adequate sealing or venting arrangements to contain and control the material.

These findings made it clear that greatly improved sealing, gas venting and evaluation of alternate outlet geometries would be required in order to successfully handle the fine materials anticipated for use in fluidized bed combustors. It also confirmed the importance of the transport properties of the material being pumped in defining the geometry required to successfully handle the material, and that some capability would be required to predict performance and geometry requirements from evaluation of materials transport properties.

Material Transport Properties Test Rigs

Earlier work in predicting feeder performance had shown some encouraging correlation with measured test results, but had used somewhat arbitrary values of materials properties to fit with measured feeder performance. Due to the significant effect of changing material properties on predicted performance, additional work was added to the planned program under this project to enable measurement of important materials properties to be made to support data correlation of the measured and predicted performance of the Stamet feeder. Coals were tested to establish these values for the conditions expected in the test feeder. Ultimately this data will be valuable in evaluation of different materials and their suitability for use with Stamet pressure feeders in different applications. The properties selected as the prime indicators required for performance prediction were: bulk density, compressibility, wall and internal friction coefficients, and permeability. Test rigs were designed and manufactured to bench test these properties.

A friction tester was made to measure friction coefficients of bulk materials against various solids, and the internal friction of the bulk material itself under typical conditions anticipated inside the Stamet feeder. (see Fig. 4).

A permeameter was made which allowed gas leakage flowrate and the rate of pressure decay through a material column to be measured at various back pressures. Pressure differences could be applied either up or down through the column. (see Fig 5).

A third device, dubbed the STA-meter was also made to measure the Solids Transport Attributes of solids materials. (see Fig. 6) This device allowed the applied force required to move a different length columns of material through tubes of various materials. These measurements could be made with various gas pressures or mechanical loads applied. The device also enabled gas leakage measurements to be taken under these conditions.

A sieve analyzer was also available to analyze particle size distributions for the materials used.

The measured values obtained were then available as inputs to calculations in support of efforts to predict feeder output, HP requirements and sealing characteristics with different materials.

Small Feeder Modification and Testing.

A smaller hydraulically driven test feeder similar in construction to the SBIR feeder but with only a 17” diameter duct was also available within Stamet. This was capable of 50 psi pressure and was mounted in the simple intermediate pressure test rig shown in Fig 7. This arrangement was used to test the effectiveness of sealing and venting modifications to contain and control solids and gas leakage prior to incorporation on the larger feeders. It also allowed preliminary testing of the effect of using straight pipe outlet geometry, as compared to the continually diverging outlets that had been used in previous tests.

The feeder was modified to enable monitoring of direct HP requirements to be made during test runs by measurement of the hydraulic pressure drop directly across the motor inlet and outlet ports. Instrumentation was added to allow dynamic measurement of outlet gas pressure and gas leakage rate to be made. The existing outlet arrangement of a simple closed tube did not allow for a mass flow measurement of material being pumped into pressure. A simple level indicator was therefore added to measure the outlet sealing column height as a test progressed, enabling feeder output flow rate to be measured incrementally by volume. Since each revolution of this feeder displaced 6.86 cu. ins of material at inlet conditions, compression and slippage effects could be assessed.

This test feeder was also modified to incorporate seals on the disk OD to prevent the large amount of material spillage of material from the feeder duct that had been experienced on earlier tests. Since the expectation was that the coal to be used in the final pressurized fluidized bed combustors would be in a fine granular or pulverized condition and would readily flow or potentially flood through small gaps, flexible seals were necessary to enclose and contain the feeder duct.

Further modifications added gas vents in the transition from the feeder duct to the outlet pipe. The vents were intended to allow gas diffusing through the outlet sealing column to be vented prior to entering the feeder duct section. This was to avoid any tendency for the gas leakage to aerate material in the duct and upset the locking of the material necessary for correct feeder operation. It also precluded any gas leakage reaching the feeder inlet and affecting the incoming material flow. These vents comprised four 2" diameter sintered bronze porous disks fitted into the circumference of the outlet pipe close to the feeder body. Enclosed cavities behind the disks were connected via tubing through a flowmeter to a vacuum source, so that controlled suction could be applied and the gas leakage rate measured. The pore size of the sintered bronze material was selected to allow maximum gas flow to be achieved while preventing any solids material from passing through.

Similar modifications were proposed for inclusion on the larger feeders at considerable expense, so testing was carried out to evaluate their effectiveness in the small-scale unit prior to incorporation in the larger feeders.

Stamet had available an ample supply of pulverized coal, and this was chosen for the initial testing so that any shortcomings in the sealing and venting systems would be exposed by the readily fluidizable material. The testing of the small 17 in diameter feeder confirmed the effectiveness of the sealing and venting modifications. Comparisons of the material flow and gas leakage agreed well with those calculated using the measured material transport properties of the coal.

The measured values for consumed HP tended to be lower than those predicted by calculation, but this could, at least in part, be explained by the testing rig and method used with this feeder. Since the tests were run with a continually increasing length of outlet column, the load was always increasing and a steady state condition was never achieved. This effect would result in lower HP usage than would be experienced in steady state tests. Since the magnitude of this effect could not be readily quantified, further comparisons were made on the larger feeder test rig where steady state conditions could be maintained.

The validity of the calculation approach was also confirmed through comparative testing of a food cereal mix, which had greatly different characteristics than the coal. This produced significant differences in performance, but, even so, the results for the cereal mix also agreed with the predicted calculated values based on the measured properties.

0230 Feeder

A series of feeder tests was then undertaken on the 0230 Stamet feeder to extend the range of data available for correlation with predicted performance.

The most significant limitations of the smaller intermediate pressure feeder test arrangement were a 50 psi pressure limit and the inability to maintain a steady state load condition. These shortcomings were overcome in the arrangement used for these tests, which enabled steady state conditions to be measured at pressures up to a rated 250 psi. The high pressure test rig arrangement used for this series of tests was the same as that described earlier. Updated instrument and data acquisition systems had been added to this high pressure test rig so this series of tests also provided an opportunity to check out the revised monitoring equipment.

The 0230 feeder was modified to handle and seal fine coal by providing radial seals on the disk periphery and improving the internal sealing between inlet and outlet. Gas venting was provided through the cast outlet horn, using similar sintered bronze disks as in the smaller pump. In this case, in order to position the vents as close to the feeder duct as possible, a series of seven 1in. diameter disks were positioned around the cast outlet horn wall at this point. The smaller diameter disks were used to allow close conformance to the small surface radii of the horn in this area. Also, due to the reduced unsupported dimension, the smaller diameter disks were stronger and more capable of withstanding the greater particle pressure that would be experienced when feeding into higher gas pressures. Seven disks was judged to be the maximum that could be accommodated without compromising the strength of the horn in this location. An additional gas venting system was positioned between the feeder inlet and outlet. This provided a 2in diameter pipe fitted into the outer wall of the duct, and incorporating a 2in diameter sintered bronze filter disk, so that any excess gas diffusing past the horn vents and beak could be vented before reaching the inlet port. Both venting systems could be connected to flowmeters and vacuum systems as before.

The outlet abutment geometry was revised to improve sealing and increase the strength of the part as some distortion had been experienced in earlier testing. New outlet geometry was designed based on the results from the small (17 in diameter) feeder and available theoretical analysis, to provide a controlled solids seal of the fine coal at the available gas pressure. This outlet design was a compromise to balance adequate sealing of the selected coal with minimal outlet restriction and hence HP requirements, while still easily mating with existing components without major machining or alterations to the installation being required.

The integral cast outlet duct diverged to a diameter of 9.5ins so any straight pipe section had necessarily to be greater than this, since any reduction of cross-section would result in lock-up of the system. Using the data obtained from the materials transport testing of the coal, the required HP and gas leakage were estimated for varying lengths of straight 10 in internal diameter pipe following the divergent section. Since the HP increased exponentially with the length and the leak rate decreased exponentially with the length, a compromise was indicated, and a 16 in straight length of 10 in diameter pipe was selected as the optimal geometry for the tests.

The feeder was installed in the high pressure test rig shown in Fig. 2, and a series of tests of this modified 0230 feeder and installation was conducted, leading to the successful pumping of the fine coal into 180 psi gas pressure. These tests demonstrating good control of gas and coal leakage and this result was demonstrated to be repeatable and controllable.

However, it was noted that, as the feeder speed was increased, the rate of flow of the coal reached a limit and at higher speeds was lower than expected. Investigation established that this was due to limitations on the rate at which the material could free flow from the hopper and through the inlet of the feeder under gravity. A series of tests and modifications effectively doubled this rate limit, but the flow was still unable to keep pace with the feeder at higher speeds.

Subsequent testing of this outlet arrangement with the coal supplied from Wilsonville did not yield the same results. The coarser coal particles flowed more easily from the hopper into the feeder so that higher flowrates were obtained, but the material did not seal as well as the finer coal at the outlet. This resulted in poor initial compaction of the outlet seal allowing more gas leakage, which tended to overpower the available vent system. The free flowing material also rat-holed easily so the outlet seal was not always stable and periodically control could be lost.

Analysis based on the performance correlations to date indicated that the best approach to correct this problem was to use a smaller dia outlet pipe with a greater length to diameter ratio. This would have the effect of increasing the material compaction and lowering the gas leakage rate. However, this change could not be readily accommodated on the 0230 feeder since the design incorporated a one-piece cast outlet horn which expanded to a 9.5 in diameter. The testing was therefore switched to the SBIR feeder, which would allow a smaller outlet to be fitted.

SBIR Feeder

The modifications required to the feeder internals to incorporate disk seals, gas venting and improved outlet configuration were identified based on the latest available data. Three alternative outlet geometries were made available for testing on this feeder to allow direct comparisons of outlet configuration changes to be made while other variables were held constant. These were the continual divergent geometry originally tested on the 0230 feeder; a shorter divergent section followed by a straight 10” diameter pipe similar to the one that had successfully sealed the pulverized coal on the 0230; and a straight square section tube which mated directly with the feeder body and provided minimal divergent section.

A 2in diameter vent was fitted between the inlet and outlet ports, as had been done on the 0230 feeder. However, the first two outlet arrangements used the original divergent section, and the low wall thickness precluded fitting sintered bronze filters in the wall as had been done in the outlets on the other pumps.

The third arrangement, using the square outlet tube, had an ample wall thickness to accommodate filters close to the feeder outlet. In this case, eight 1 in. diameter filter disks were fitted, two on each wall of the tube. This square tube was made as long as could be accommodated within the test rig so that tests could be made with the maximum compaction available in a straight duct. For reduced length tests an auger was to be used inside the tube to break up the outlet column at a pre-determined position. This arrangement is shown in Fig 8.

During October 1999 the modified SBIR feeder was assembled and set up on the test rig. Testing commenced using the granular coal that had been previously supplied from Wilsonville. During the early tests damage occurred to the disk seals. These had been made of a teflon based material to evaluate a lower cost material against the UHMWPE that had been used on the other feeders. The seals failed in compression due to the poor compressive strength of the teflon material relative to the UHMWPE, so the seals were replaced with UHMWPE versions which then proved adequate for the application.

Following this, the first test runs with gas pressure applied to the outlet were carried out in November 199. However, as gas pressure was applied a mechanical failure occurred in the driving torque-hub of the feeder. The cast gear housing had cracked and failed. This failure occurred at a torque value much lower than the hub rating, so it is believed that the crack was initiated during earlier testing of this feeder and then continued to grow, leading to the subsequent failure. Replacement parts were costly and on a long lead time, so a decision was made to re-design the feeder to incorporate a larger, stronger torque hub which was available from a different test feeder. This change would also prevent a recurrence of this failure mode during the remaining test program and provide a stronger, more flexible test platform for future work.

The feeder design was therefore modified to accommodate the larger torque hub and the necessary parts obtained. Fresh material was obtained from Wilsonville and the final series of tests with the optional outlets were then carried out as described below.

Results & Discussion

Initial Evaluation

The initial feeder testing using the Wilsonville supplied coal was carried out in the 0230 feeder. These tests used a continually diverging outlet from the duct up to a 16 in diameter. This was similar geometry to that which had been successful when pumping the selected ¼”- coals up to 210psi. (see Fig 1) The initial test runs indicated considerable problems in handling the Wilsonville material. The coal had poor sealing characteristics, and leaking gas blew out from the feeder duct carrying a considerable amount of coal with it. In an attempt to contain the leakage, the feeder casing was enclosed and a vacuum system with an extraction bag was fitted to contain the coal and handle the gas flow. However, it was found that the gas feed system on the test rig had insufficient capacity to compensate for the very high gas leakage rates experienced with this coal and outlet geometry, so that gas pressure could not be maintained. (Leakage was measured at up to 130scfm at only 40psi pressure differential) Also, promoted by the high rate of gas flow through the system, an excessive amount of coal leaked from the feeder duct rapidly filling the body so that purging was required to empty the body cavity.

Instabilities were also observed in the outlet solids seal, with periodic ratholing preventing a stable outlet seal being maintained in the divergent outlet duct. A free weight was used to apply an additional load to the surface of the outlet coal plug in an attempt to compress the coal uniformly and eliminate the rat-holing leakage. However, little effect was observed on compaction and the tendency to form ratholes remained.

This first series of tests had therefore shown that the Wilsonville coal was very free flowing, easily maintaining flow from the hopper into the feeder inlet. It was readily gripped & pumped by the 0230 feeder, but, even in zero gas pressure tests, coal spilled through the clearances between the body and the feeder duct as it rotated. With gas pressure applied, the coal was found to be very permeable, and large gas leak rates were observed through the coal outlet plug. The escaping gas then carried large amounts of the fine coal with it. The easy pouring characteristic also permitted the intermittent formation of rat-holes or leak paths through the outlet plug. Initial attempts to prevent this occurrence by applying an even load to the surface of the outlet solids seal were unsuccessful.

It was therefore apparent that the feeder would require improved sealing of the gaps between the rotor and the body to contain the fine coal, and the addition of venting to allow gas leakage to escape from the system without causing excessive material leakage. It was also clear that the continually diverging outlet geometry did not allow an adequate outlet seal to be obtained with this material, although other coals had been successfully handled with this geometry. It was clear that alternate outlet geometries would need to be investigated. These findings also emphasized the need to develop the ability to predict the performance of the Stamet Posimetric feeder with different materials, so that outlet configurations could be selected based on the application. Since it was known that improved material compaction could be obtained using a straight outlet pipe, this static outlet geometry arrangement was selected for investigation to determine what would provide an adequate seal with this material.[1]

Material Transport Properties Test Rigs

As stated earlier, testing was carried out to measure the transport properties of the materials pumped so that some correlation may be obtained to aid development of calculations to predict feeder performance. The measured parameters of friction, compressibility and permeability can then be applied to the feeder performance calculation to assess accuracy and allow refinement of the approach. Following is a brief description of the approach used to calculate feeder performance.

The calculations forming the basis of the current analysis estimate the load on the feeder from three sources of resistive torque. The first source is the 'Brake Shoe' effect, which is the frictional effect produced by the pressure of the particles against the glide plate. The particle pressure distribution along the glide plate is assumed to be parabolic (as an approximation for the possibly truer exponential form), reaching a maximum at the feeder outlet. By using the parabolic distribution an allowance is made for the fact that the particle pressure is higher at the discharge than it is at the inlet and the distribution results in the average particle pressure being taken to be 1/3 of the Maximum Particle Pressure.

The Maximum Particle Pressure is taken to be a function of the outlet gas pressure, the effect of the friction of the discharge duct and the piston multiplying effect of the larger divergent discharge area.

The second resistive force, the 'Tangential Load', is taken to act directly against the solids in the discharge duct and calculated as the Maximum Particle Pressure multiplied by the cross sectional area of the discharge duct.

The third force is the 'Brake Pad' force. This force is assumed to be due to the frictional effects of the solids leaving the disk and traveling at a speed which is lower than disk speed, so that the disk has to act against the friction between the solids and the disk. This effect takes place in the discharge segment and the calculator includes the calculation of the area of this segment shaped disk pad itself (ie. of two 'half segment' pads). The pressure acting on the disk pad is assumed to be equal to the maximum particle pressure and to act at the mean duct radius.

The sources of friction described above can be calculated from particle pressure and friction coefficient information. However, there are additional losses to be accounted for,

[1] It should be noted that, at this point, consideration was given to the use of an active compaction system with feedback control that would optimize outlet compaction to maintain a reliable seal. However, this would add a level of cost and complexity to what is in essence a simple, single moving part mechanical device. At this time it was decided that such development was beyond the scope or available funding of the current project, though with current advances in electronics and feedback control technology this approach may still be a viable option for future development to handle difficult materials.

primarily the energy used in shearing the solids internally and friction losses against the divergent discharge cone. Theoretical estimates of the magnitude of these effects are difficult and require several further simplifying assumptions to be made. The validity of such efforts can then only be evaluated by comparisons of predictions with actual readings taken within feeders under test.

For a calculation to successfully predict the requirements and performance of a pressure feeder with a solids material seal on the outlet, the approach needs to also allow calculation of the maximum solids pressure from the outlet conditions. A spreadsheet was therefore developed, initially retaining the assumption of parabolic pressure distribution through the duct and outlet transition, but calculating the material loading effects starting at the end of the outlet seal and calculating back down through the outlet duct to estimate the actual outlet particle pressure generated by the outlet resistance. This requires further assumptions to be made for the reaction of the material in the outlet pipe with the pipe wall and to the applied gas pressure in order to calculate the resulting loads. For the first iteration gas pressure was assumed to decay linearly through the material column. This and the weight of the material then allows the resulting force below a layer of material to be calculated. Depending on the ratio of axial to resulting radial force (Z factor) and wall friction coefficient, the resulting frictional resistance can be determined for that layer. By following the calculation progressively down layer by layer through the outlet material column a value for the load at the base of the column can be arrived at. The permeability of the outlet material column governs the rate of gas leakage, so if that property is known, expected leakage rates can be calculated and any vent system sized accordingly.

The spreadsheet was set up to allow input of differing friction coefficients to be used for the feeder duct, glide and outlet pipe, along with a Z factor for the material. These properties were individually measured to give a practical basis for the values used in the performance prediction, so that the assumptions and calculations used in the prediction can be truly tested. Future work will refine the assumptions and calculations based on the correlation of the performance prediction with actual measured results.

Small Scale Feeder Results

After fitting the disk seals, preliminary testing was carried out to establish baseline HP requirements to drive the feeder empty so that this value could be isolated from the additional load to pump the materials. Test runs were then successfully carried out feeding coal under a range of operating conditions into gas pressures up to 50psi. A pulverized coal was chosen for this series of tests so that any potential problems with sealing material spillage or plugging of vent filters would be readily apparent. The effects of the outlet column sealing plug length and applied gas pressure on leakage and drive HP requirements were then evaluated.

The disk seals worked well to contain the fine coal used for these tests. Once a minimum length of sealing plug had been established in the outlet duct, gas pressure could be applied to the top of the column. The vents placed at the feeder outlet were able vent the gas leaking back down the coal column, successfully limiting the gas pressure at the feeder outlet so that leakage did not flow back through the feeder duct and affect material flow at the feeder inlet. The measured gas leakage rates through the outlet column were in line with the anticipated values based on the permeability measurements taken prior to the feeder testing.

As anticipated, the HP required to drive the feeder rose rapidly as the outlet column length and applied gas pressure increased. However, some inconsistencies were present in the results from tests carried out at apparently the same conditions. It is believed that this resulted from the fact that a stable condition cannot be maintained in the small test feeder as configured, since the outlet column length is always changing. Also the feeder speed varied somewhat during these initial tests, slowing as the load increased. This effect, which was due to characteristics of the hydraulic system being used to drive the feeder, resulted in some stick/slip effects in the outlet column. Consequently tests at nominally the same conditions did not necessarily have the same load/time history leading up to that point in time, so that compaction of the coal in the feeder duct and outlet column, and hence the friction and HP requirements, were not the same in each case. In these early tests this variation was borne out by qualitative examination of the packed coal when the test rig was stripped and cleaned after the tests, with harder packed coal being found after tests which had indicated higher HP readings.

A further effect can be anticipated from the continually increasing load through the duration of a test. At no time did we reach the condition where the complete solids material in the feeder duct and outlet column was pumped under the full load existing at the time the readings were taken. The coal passing through the feeder earlier in the test had not experienced the same resistive load as that passing through later, so the potential maximum resistance to flow may never have been reached. The test rig for the larger feeders provided for a fixed length outlet sealing plug and material collection and weighing within the pressurized outlet. Therefore, in the large feeder tests steady state conditions should be attained and this effect will not be present once steady state conditions have been maintained long enough to flush coal through the entire system.

The feeder output volume measurements showed volumetric efficiencies falling to approx. 70% under load. This was consistent with the expected values based on the compressibility of the coal entering the duct and did not indicate that any significant slippage was taking place inside the feeder.

As described earlier, the calculations to predict the performance of the feeder, and in particular the torque and power requirements for a given condition, are based on the work done to date on the mechanics of flow through the feeder, and the restrictions to forcing a column of material through a pipe. This calculation was then run using the materials property values measured in the various test rigs for the coal and the wall materials used in the feeder and outlet. In this case a further assumption was made of a 50% efficient divergent in the transition region from the feeder duct outlet to the round outlet pipe.

This combination of data and assumptions results in predicted HP levels somewhat higher than the readings obtained in the initial tests. This is what would be expected since, as has been previously stated, the testing never achieved a condition where the material had been fully loaded throughout its travel through the feeder. Although much refinement and confirmation of the assumptions is needed, the correlation was very encouraging at this stage. However, it has only been tested for a limited range of operation and materials, so work is needed to test other conditions and check the correlation across a broader range of operating conditions.

To provide some checking on the range of validity of the calculations, some tests were carried out using a food cereal mix instead of the coal. This material had much lower friction coefficients and different permeability, so that the performance obtained was very different than with the coal. However, the performance predicted based on the materials properties was still in line with the measured results, giving some assurance that the calculations could be applied on a broader basis.

These same predictive calculations were then applied to the larger scale feeders to define the outlet designs required for the higher pressure tests, since it provided the best input data available at the time.

0230 Feeder Results

Following the modification of the 0230 feeder to provide internal sealing and gas venting as described earlier, a rotary torque transducer was incorporated into the drive train to allow direct torque measurements to be obtained. After installation of the 16 in long by 10 in diameter straight pipe section in the outlet, a series of tests was conducted at increasing outlet pressure levels. This series of tests lead to the successful pumping of the pulverized coal into 180 psi gas with minimal gas or coal leakage. This result was found to be controllable and repeatable. Higher gas pressure levels could not be attained due to the drive torque limitations on the gear train being used with this feeder.

The gas leakage rates experienced and the HP levels required to drive the feeder were in line with the predicted calculated values, although some variation was observed from test to test.

However, the testing identified low volumetric efficiency levels for the feeder at higher speeds, so the potential material flowrate was not achieved. Investigation determined the cause to be on the supply and inlet side of the feeder. This shortfall on the supply side also affected the filling of the feeder duct and this in turn affected the available grip, material pressure and sealing ability and ultimately the HP required for operation, resulting in the test-to-test variations noted above.

To improve this situation, a series of tests was carried out to determine the supply capacity of the existing hopper and supply pipe. These tests determined that the existing hopper and downcomer arrangement could not deliver the coal being used to the inlet of the feeder at the required rate to maintain a full inlet. The existing hopper incorporated an internal baffle arrangement intended to prevent the weight of the material in the upper portion of the hopper bearing down on the lower section and causing excessive compaction and bridging of the coal in the lower cone section. The light coal particles being used were unable to flow past the baffle at a sufficient rate to keep pace with the feeder, so the baffle was removed. With the addition of a stirrer to prevent compaction and bridging, and the replacement of the lowest section of the hopper with a mass flow design a doubling of the maximum flowrate was achieved.

The initial testing also showed that the effectiveness of the venting system in the outlet horn was limited. The fine coal sealed so well that it was difficult for the gas that was flowing between the particles to migrate to the vent locations. An additional vent was installed between the feeder outlet and inlet to allow migrating gas to escape without interfering with the material inlet flow.

Further testing with this modified arrangement showed a significant increase in the feeder throughput. Full capacity (100% volumetric efficiency) was achieved at approximately 60% of full speed with no gas load applied. Further modifications to the inlet pipe were incorporated but we were still unable to maintain full capacity when running the feeder at full speed. This is believed to be at least in part due to the fine particulate nature of the coal which limits the rate at which it can fall through a pipe and then transition into the feeder duct. Observation of the flow down the inlet pipe was possible via a video camera, and it was seen to periodically speed up and slow down. Occasionally some air was seen to bubble back up through the pipe, restricting the incoming material. Since the feeder had an open vent between the inlet and outlet ports, this air was believed to be entrained in the incoming material and then venting back up the inlet as the material settled in the feeder duct. Additional venting was added to the inlet side of the feeder to help to de-aerate the material as it entered the feeder duct and limit the amount of air flowing back up the inlet pipe.

A program of testing to investigate and improve the flow characteristics of the inlet & transition regions will be implemented, but this could not be readily carried out on the equipment to hand or in the time available. Since it was felt that this should not be a significant barrier to completion of the work under this grant, this program was held for the future and work continued to progress towards the final series of feeder tests on the SBIR unit.

SBIR Feeder Results

As discussed, the data obtained from the 0230 feeder tests was used to correlate with the predictions derived from the materials data and improved agreement obtained. This data was then used to finalize the modifications to be incorporated into the SBIR feeder for the final high pressure testing program.

As with the 0230, the SBIR feeder was modified to incorporate disk seals for coal containment within the feeder. The radial seal design used in the small-scale feeder and the 0230 could not be incorporated into the SBIR feeder due to space constraints, so an axially loaded design was used. A material change was also made to the seals to evaluate a potential cost saving and possible reduction of seal friction loss. A teflon based material was selected for evaluation as being lower cost with a reduced coefficient of friction. Although the wear properties were not as good as the UHMWPE material used on the other feeders, no significant wear had been observed on the seals to date, so it was decided to evaluate the teflon.

Outlet configurations similar to those used on the 0230 feeder were available for the SBIR feeder. Also, based on the earlier tests with the Wilsonville coal, an additional outlet using the smallest cross-section outlet duct that could be accommodated was added. Since the outlet from the feeder body was a rectangular section, a square pipe section at 45 degrees to the feeder body provided a good match. Since the feeder had been tilted at 22 ½ degrees to the vertical during earlier testing, this resulted in an outlet pipe at 22 ½ degrees from the vertical. Since the biggest issue with the Wilsonville coal was establishing a stable seal on the outlet, this pipe was made the full length that could be accommodated within the confines of the mating components of the test rig, resulting in a maximum median length of 21 ins. This pipe fed into a tee and bend arrangement to mate up to the same valve and pressure vessel arrangement as the other outlets. An adjustable auger was fitted inside the pipe so that the outlet column of coal could be broken up at any pre-determined height within the pipe to give an effective seal length less than the maximum available. Calculations indicated that the required column height for acceptable sealing and HP was within the range of adjustment provided by this arrangement.

In October 1999, the first series of tests were run with no gas pressure to establish base friction, torque and speed relationships. During this series of tests a drift of the baseline values was noted. Upon investigation it was found to be due to a failure of the disk seal material. In operation the high compressive stresses applied in the axial seal design resulted in the seal material yielding and creeping, with consequent binding and loss of seal. New seals were therefore made from the same UHMWPE material that had successfully been used in the other feeders previously tested. At the same time, the disk sealing was modified to provide an adjustable support ring behind the seal to allow seal pre-load to be adjusted. Locating pins were included to attach the seal ring to the support ring at several locations to evenly distribute torque loads around the circumference and so prevent excessive compressive loads on the material leading to distortion and bunching, which was the failure mode experienced with the teflon seals. These were fitted and the baseline testing repeated successfully.

By monitoring the torque rise as the pipe filled and then stabilize at a steady, maximum length as the material was pumped into the vessel, the effect of the square column length was evaluated. The results were again in line with calculated expectations.

A series of tests was then begun, gradually increasing the gas pressure applied to the outlet. During this series of tests a major failure occurred in the torque-hub used to drive the feeder. Although the torque readings obtained during this testing were somewhat higher than had been predicted, this failure occurred at a torque level well below the actual rating of the drive. Upon stripping down the unit it was found that the cage retaining the outlet gears had cracked. Since this torque hub had been used in earlier testing at much higher loads than were applied during this test, it is believed that higher loads applied at that time must have weakened the cage and initiated cracking leading to the failure experienced here. Since the replacement parts needed were expensive and had a very long lead time, other options to replace and strengthen the drive train were investigated.

The final decision was made to modify the feeder to accept a larger drive hub that was already available in house. This had a rated torque capacity several times that of the original hub and had never been overloaded, so that this type of drive failure should not recur. The necessary redesign to accommodate this hub was completed in December 1999, and manufacture of the required parts was completed by March 2000.

Initial tests were carried out using a new sample of Wilsonville coal with the continually diverging outlet and 10 in diameter straight pipe outlets that had been tested on the 0230 with the earlier samples. This confirmed that with the new coal, these outlet arrangements were still unable to create a stable outlet seal.

The next series of tests was carried out using the full available square pipe length. As predicted for a fixed length pipe, the torque rose linearly with the gas pressure. However, it was noted that the rate of increase was somewhat higher than that predicted by the earlier calculations. These calculations were based on a round pipe at the feeder outlet, and these tests were using a square outlet tube as the being the best available fit to the feeder outlet. This difference affects the pressure loads and wall friction areas, which are responsible for the load amplification back down the pipe. Modification of the analysis to account for this difference then improved the agreement of the calculated values with the measured results, a very encouraging result in the efforts to develop sound performance prediction capabilities.

During these tests a stable seal was successfully created with the Wilsonville coal and the gas leakage was controllable through the venting system. However, as anticipated with such a long outlet column, the HP requirement rose rapidly with the pressure. For a slow speed device like the Stamet feeder, the actual torque values through the drive system are high for a given HP, and this really becomes the limiting factor in overloading the drive system. The torque ramp rate with gas pressure therefore limited the maximum pressure applied in this series of tests to 150 psi to prevent any danger of overload of the drive train or feeder components.

As stated, this was the expected result with the full outlet pipe length in use, and testing then proceeded with the auger in place inside the pipe to reduce the effective seal length within the pipe.

The auger was driven by a variable speed electric motor/gearbox, which provided a top speed of only 6 rpm. The first series of tests carried out with the auger in place showed steadily increasing torque values even though the gas pressure was held constant. When the auger location was raised, the effect stopped briefly and then recurred. This indicated that the auger was unable to clear away the material at a fast enough rate without imposing additional loads on the surface of the material column, with a consequent increase in the required torque. At the measured material throughput, the column surface would be rising approximately 0.5 ins per revolution of the auger, so the auger would be trying to peel off a 0.5 in thick layer of material.

When the auger was removed it was discovered that the end flight was bent up so would not have been doing an effective job of sweeping away the coal. This damage was believed to have been caused when the feeder had been rotated for a brief period without the auger running. The damage was repaired and the auger re-installed. To reduce the depth of cut the auger was required to make, the electric drive was replaced with a hydraulic motor, which allowed a top speed of approximately 50 rpm.

When the system was re-tested the auger appeared to work much better and a stable test run was achieved with 25psi gas on the column. However, it was found that as the gas pressure was increased to 50psi, the effectiveness of the auger was reduced and the again effect of steadily increasing torque at a steady gas pressure was observed. This can be explained by the fact that, as the applied gas pressure increased, the load on the coal passing through the feeder increased so the degree of compaction and hardness of the coal at the face of the auger increased. Although the auger could effectively remove relatively soft coal, the point was eventually reached where the auger was unable to sweep away the harder coal without imposing additional loads on the surface of the column, resulting in the observed torque increase.

The end of the auger was modified and reinforced to provide a more rigid cutting edge that was matched to the angle of incidence with the coal, and the testing recommenced. However, at higher pressures, stable conditions could only be maintained for a short period of time before the torque would begin to rise, indicating that the auger was still not working effectively. This effect became more pronounced as the applied pressure was increased and resulted in an increased hardness of the coal surface making it more difficult to break up. When a test was allowed to continue under these conditions the torque continued to ramp up due to the increasing outlet resistance until the feeder drive motor would finally stall out. At the speed and condition the variable speed drive was running, it was capable of approximately 20 HP before this stall condition occurred.

Some limited test data was then obtained by taking short runs and recording data until the torque began to ramp up due to the increasing load from the ineffective auger. This test data indicated that the square pipe outlet was capable of providing a stable outlet seal with the Wilsonville coal, and that if an intermediate pipe length could be controlled, the SBIR feeder should be capable of pumping the material into 450 psi. Such an arrangement on the existing feeder would require an estimated 15 HP to pump the coal into 450 psi of gas pressure. Thus the test data confirmed that the original estimates predicting that a square pipe outlet configuration somewhat shorter than the maximum length installed would provide a satisfactory configuration to achieve the 450 psig target pressure were valid.

Unfortunately, with the auger system being used during these tests, we were unable to achieve that condition because of the inability to run for a sufficient length of time to build a controlled seal. For a stable seal to be maintained, the coal forming the seal must be pumped under pressure so that it is sufficiently compacted to limit the gas leakage rate and maintain stability at the pressure applied. To initially reach that stable condition the feeder must be running as the pressure is first ramped up, forming a progressively stronger seal as the pressure rises. (Once the system has been initially filled at pressure, shut-down and re-start can be accomplished statically.) With the limited time the system could run before the additional auger load effect commenced and stalled the system, we were unable to reach pressures greater than 250psi

As noted above, this work has indicated that the Stamet feeder is capable of pumping the Wilsonville coal into pressure in a controlled manner, and that 450psi should be attainable with some modifications to the outlet configuration of the existing equipment.

The work reported here focussed on the use of static piping geometry to attain a controlled material seal on the outlet, and it also showed the dramatic effect that variations in material properties can have on the geometry requirements. Future work will be needed to evaluate and maximize the range of variation in material properties and operating conditions that can be handled by a given static system. [2]

[2] As noted earlier, a dynamically loaded outlet with feedback may have the potential of making a system that could handle a wider range of material variations than a simple static outlet, but at the cost of cost and complexity. Considerable further work would be needed to assess the viability and reliability of such an approach.

Conclusions

Effective sealing and venting techniques have been developed to enable Stamet feeders to handle fine granular and pulverized materials and successfully feed them into pressure in a continuous and controlled manner.

Testing to date has demonstrated the ability of the Stamet feeder to successfully feed coal into pressures up to 250psi.

The physical properties of the material being pumped have a major effect on Stamet feeder design requirements to handle and seal the material against pressure.

Those material physical properties which are important parameters in the evaluation of potential applications with Stamet feeders have been identified. They can be readily measured using simple procedures to provide data to assess material suitability in specific applications.

Calculation methods have been developed to estimate Stamet pressure feeder performance based on measured material physical properties and the requirements of the application. The calculation results correlated well enough with measured feeder performance to allow their use in selection of feeder design parameters to meet the applications investigated in this project. Further refinements should improve the level of accuracy and range of applicability of the predictions.

Testing has shown that a solids material seal can be successfully maintained by selection of an appropriate fixed piping geometry at the feeder outlet. Calculations have been developed to successfully predict the required outlet geometry to match particular applications.

Efforts to control and adjust the length of an outlet solids material seal using an auger to mechanically break up the solids column at a selected length were unsuccessful in providing adequate control at higher pressures. Further work will be required to develop a method to allow on-line adjustment of outlet solids material seal length.

The data that was obtained from the square outlet pipe tests provided confirmation that a somewhat shorter length of this pipe on the outlet would be capable of sealing the 450 psi target pressure for this project without excessive power draw.

Although the program target of 450psi has not yet been met within the time and funding limitations of this project, the work to date has clearly indicated the method and required geometry to successfully achieve the target.

	Small Feeder	0230 Feeder	SBIR Feeder
Disk O.D. (ins)	17.4	30.0	32.375
Duct X-Sect Area (sq.ins)	1.725	2.932	3.198
Displacement per rev. (cu.ins)	86.2	260.2	309.0

Table 1. Feeder Sizes.

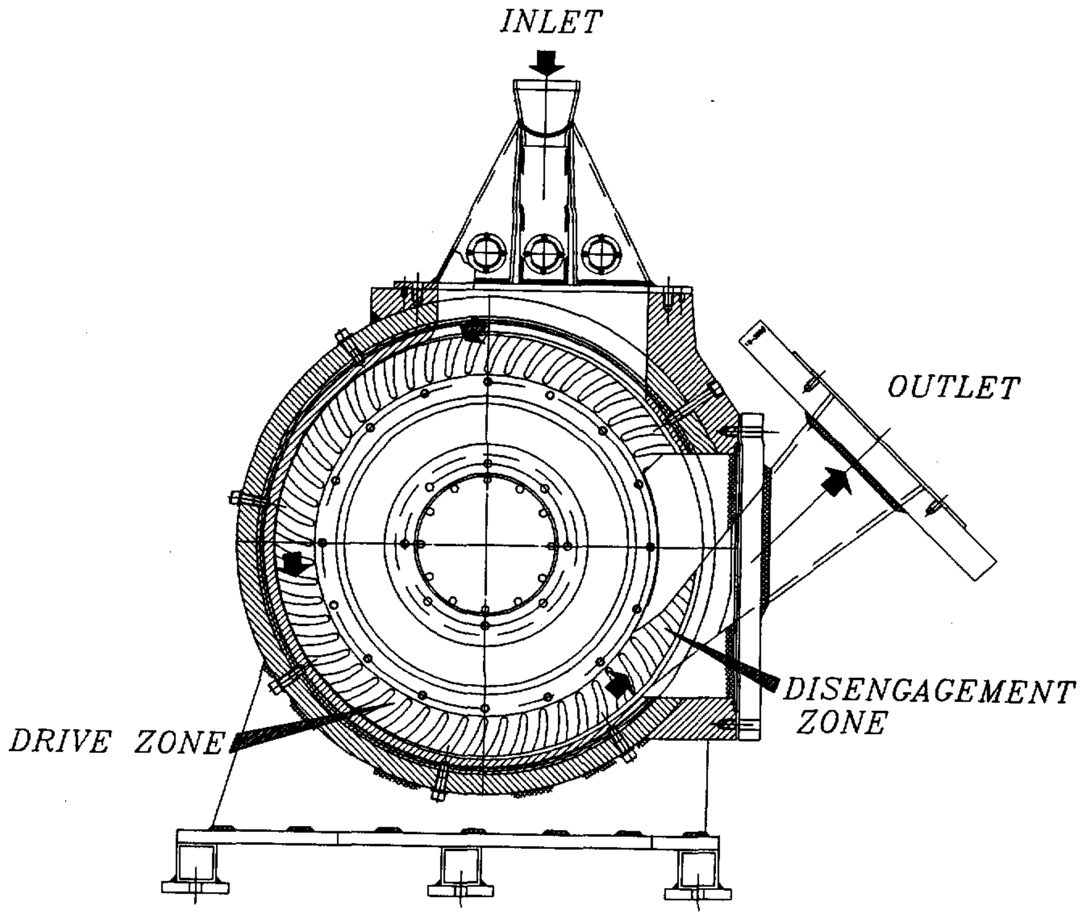
	Wilsonville Coal	Pulverized Coal	Cereal Mix.
Atmos.Bulk Density, lb/cu.ft	49.5	44.5	33.8
Compressibility @ 100psi, %	93.8	78.8	59.5
Coeff. of Friction (Internal)	0.33	0.28	0.19
Coeff. of Friction (against SS)	0.35	0.39	0.21
Permeability @ 100psi, $ft^4/lb/s \times 10^5$	2.38	0.13	4.20

Table 2. Significant Material Properties.

Feeder	Material	Gas Pressure, psi	Material Flowrate, lb/min	Power , HP	Vol. Efficiency %	Gas Leakage, scfm
Small Feeder	Pulverized Coal	50	0.7	0.32	76	0.5
Small Feeder	Cereal Mix	50	0.47	0.12	66	1.0
0230	Pulverized Coal	180	3.0	5.2	62	2.5
SBIR (10" pipe outlet)	Wilsonville Coal	75*	4.5	2.5	86	20+
SBIR (square pipe outlet)	Wilsonville Coal	210**	4.9	21.5	81	7.7

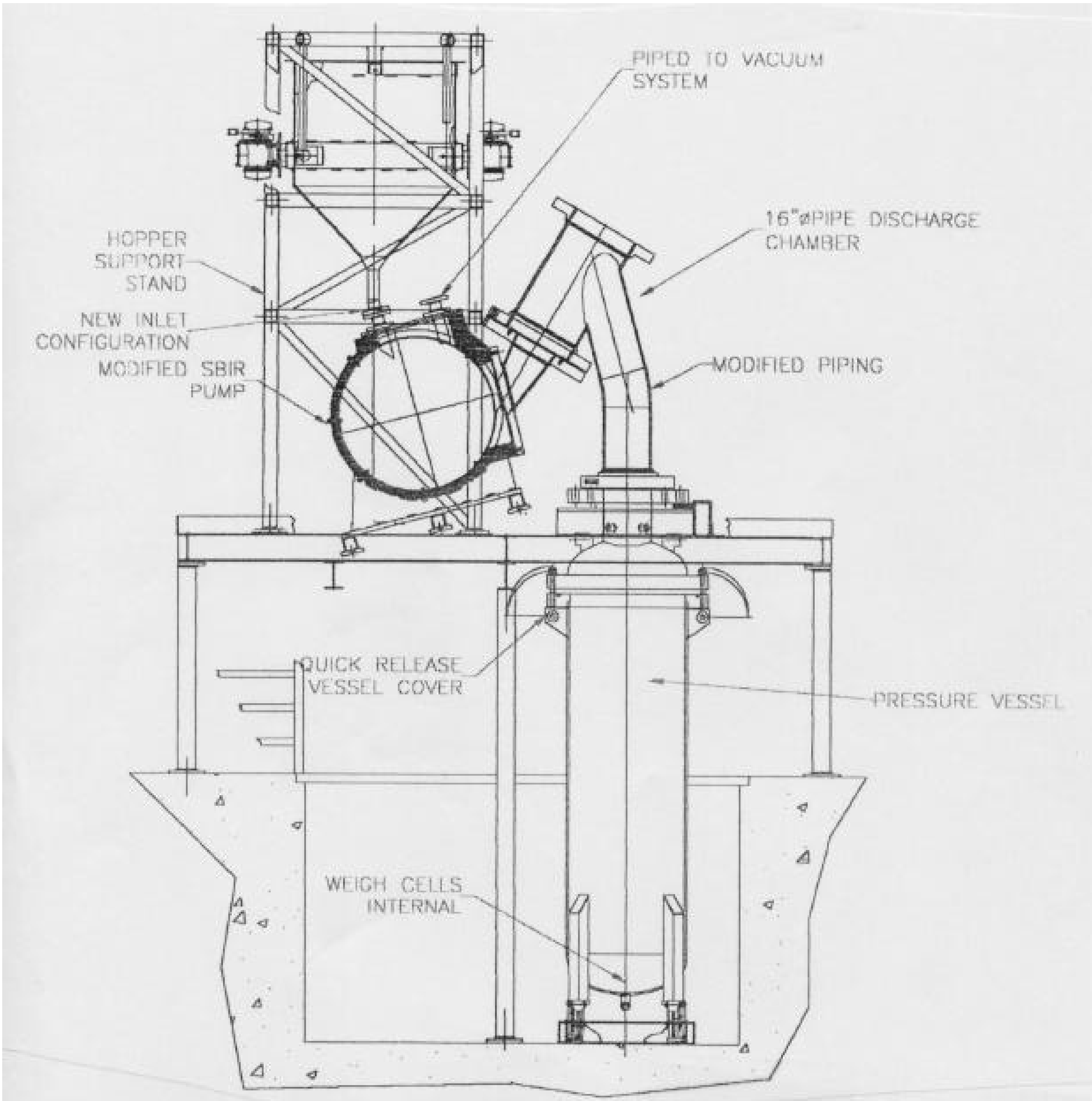
* Pressure achieved limited by outlet seal stability and high gas leakage rates.
** Pressure achieved limited by run time.

Table 3. Typical Feeder Test Data.



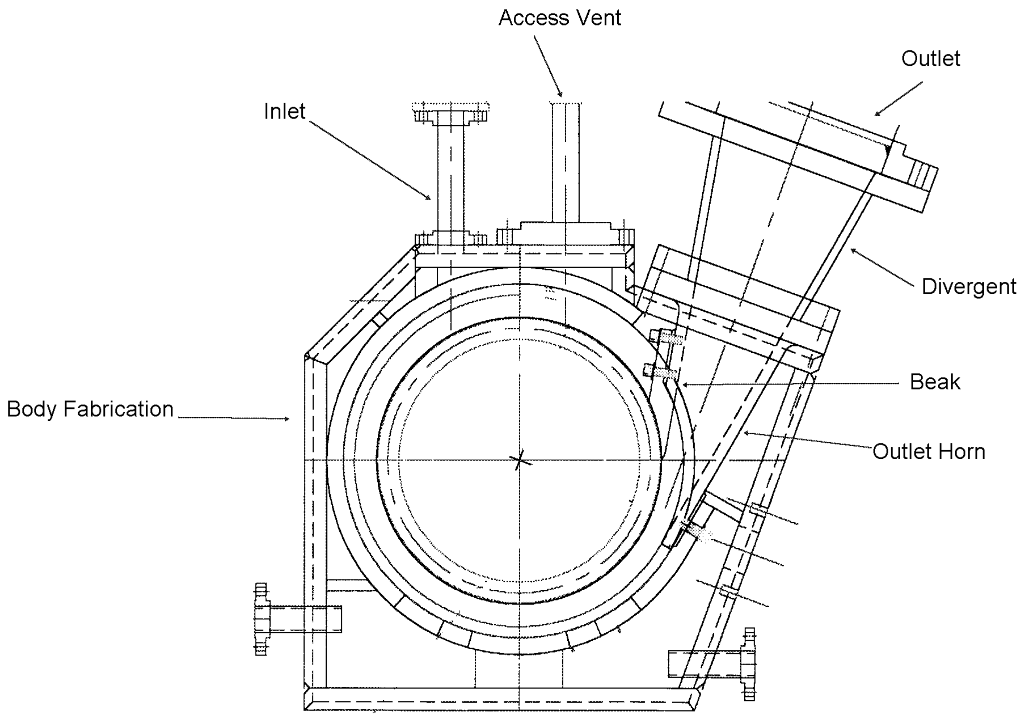
Cross-Section of Stamet High Pressure Feeder

Fig. 1.



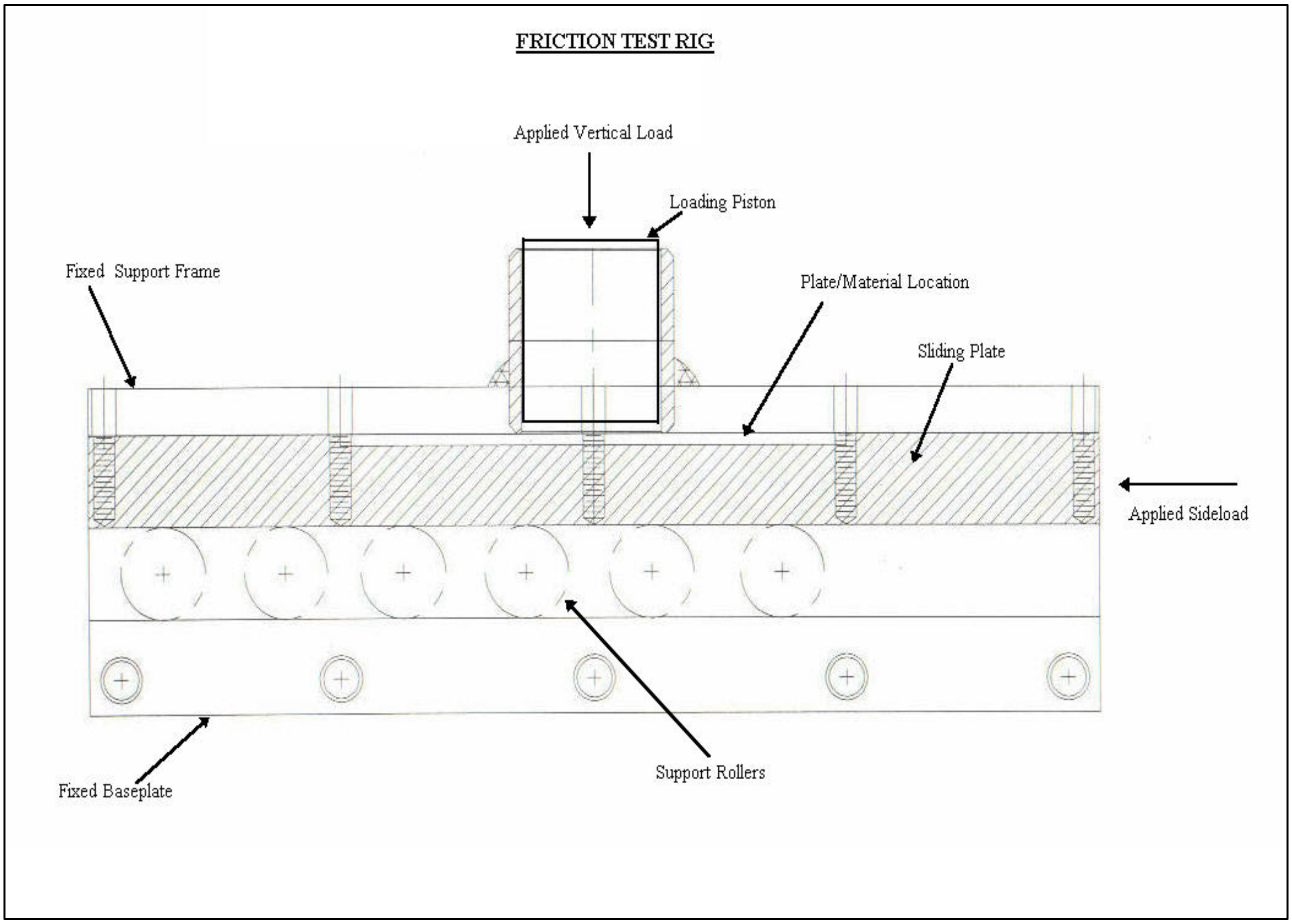
Stamet High Pressure Test Rig

Fig. 2.



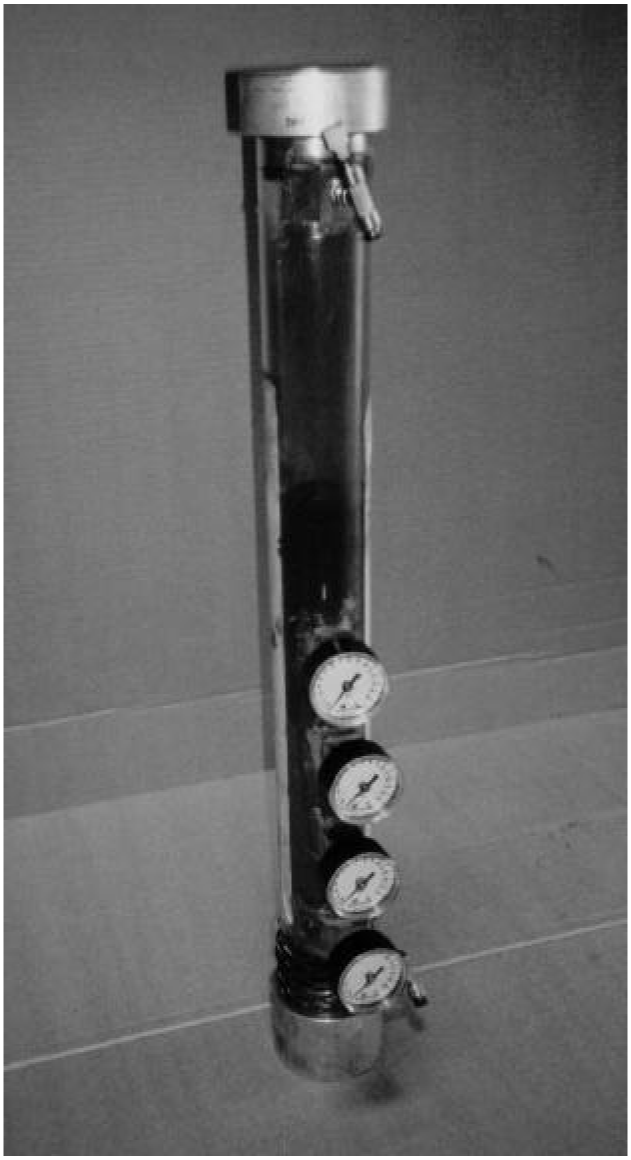
Stamet 0230 High Pressure Feeder

Fig. 3.



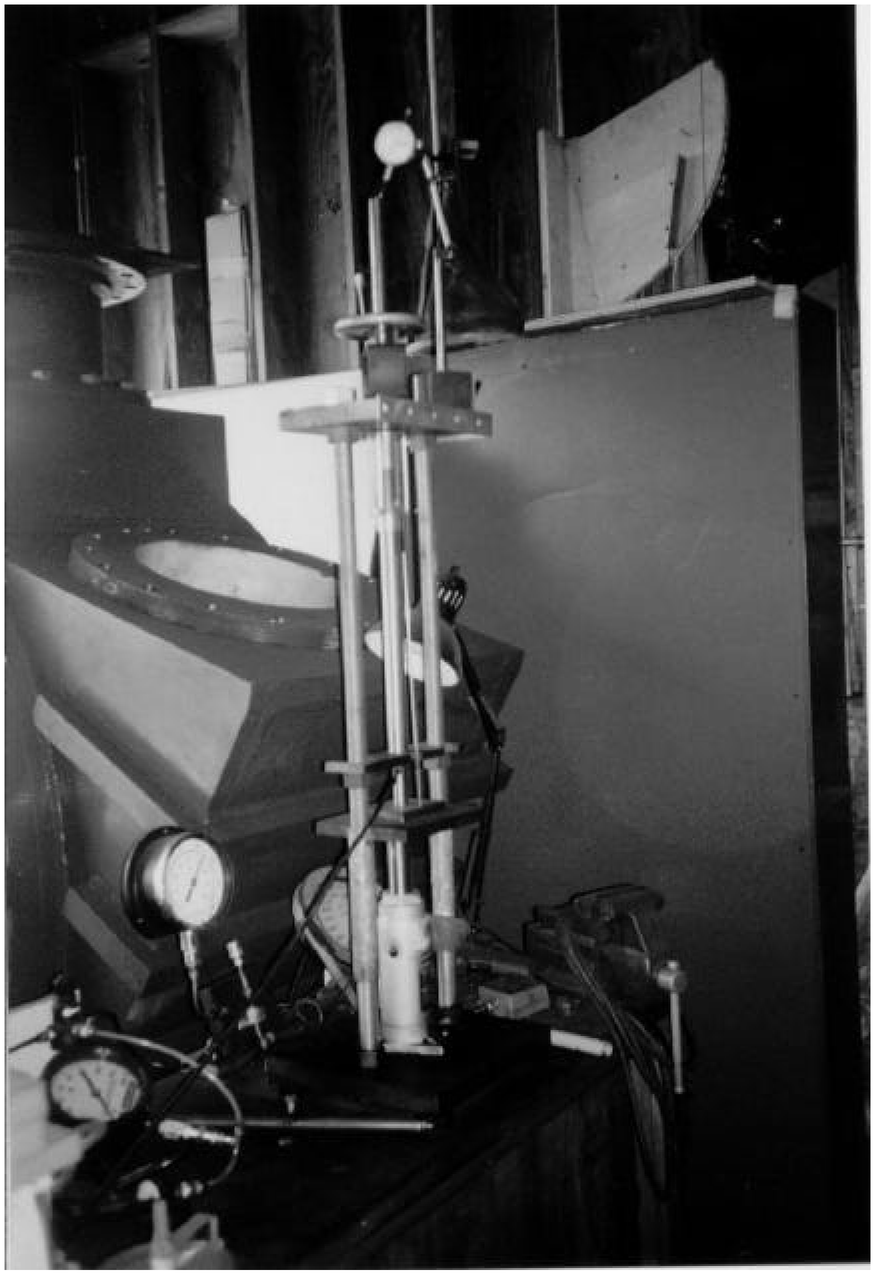
Cross Sectional View of Friction Tester.

Fig. 4.



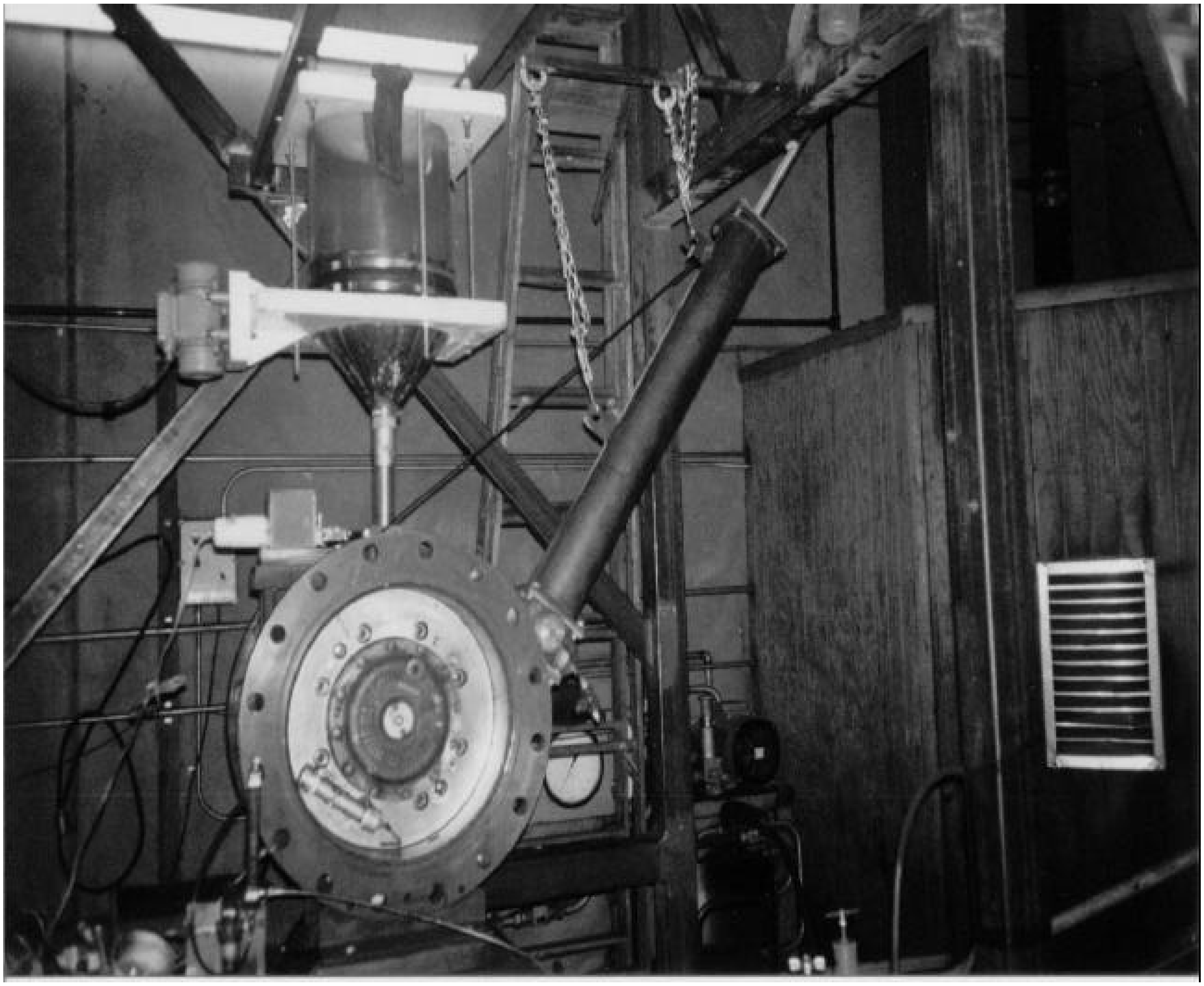
Stamet Permeameter.

Fig. 5.



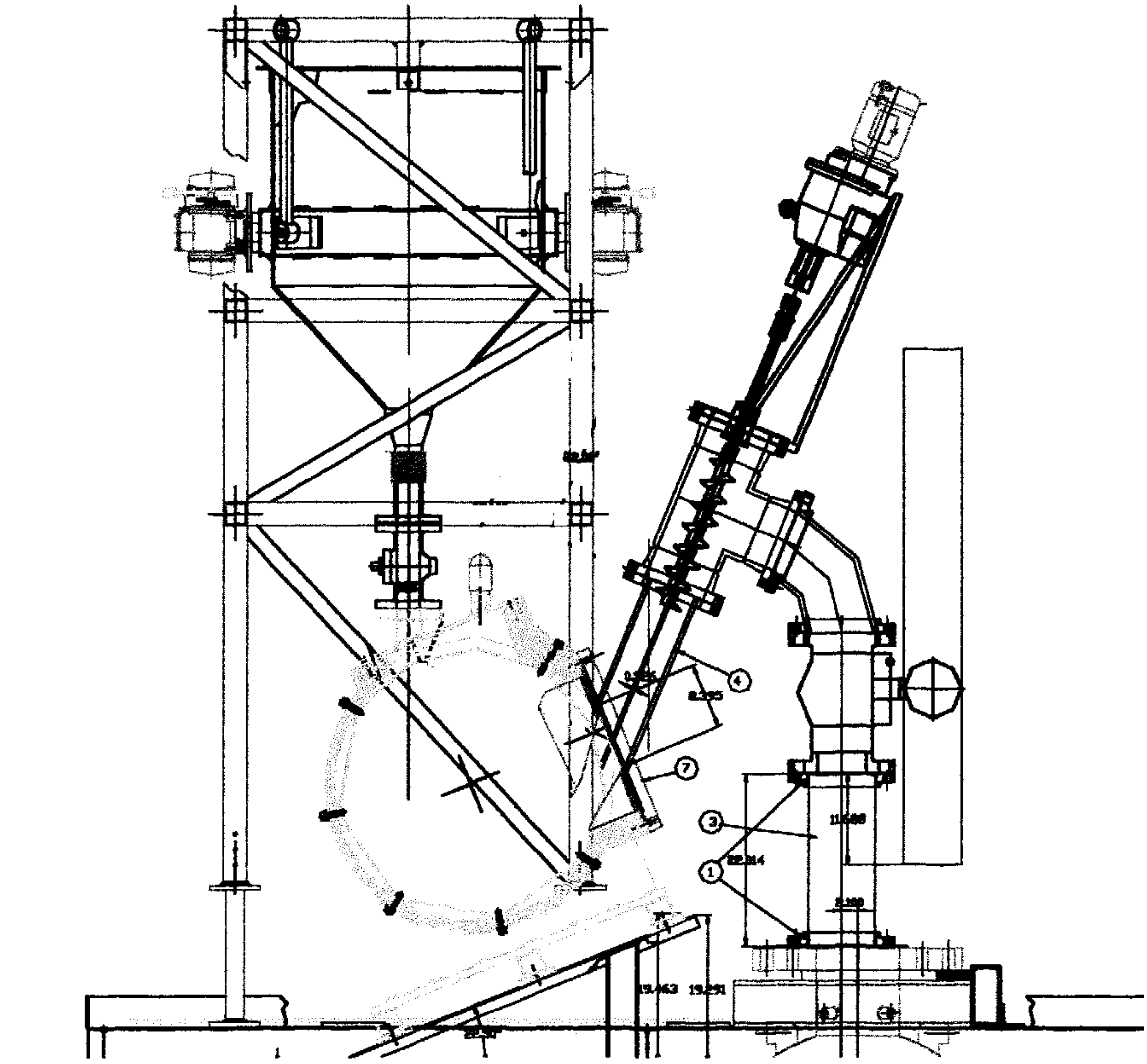
Stamet Solids Transport Attributes Meter (STA-meter)

Fig. 6.



Small Scale Stamet Pressure Feeder and Test Rig.

Fig. 7.



Square Tube Outlet with Auger mounted on SBIR Feeder.

Fig. 8.