RI 8825

Bureau of Mines Report of Investigations/1983

# Slurry Transport Properties of Graded Coal Waste

By R. W. McKibbin, R. R. Backer, and R. A. Busch

UNITED STATES DEPARTMENT OF THE INTERIOR

Report of Investigations 8825

# Slurry Transport Properties of Graded Coal Waste

By R. W. McKibbin, R. R. Backer, and R. A. Busch

UNITED STATES DEPARTMENT OF THE INTERIOR
James G. Watt, Secretary

BUREAU OF MINES
Robert C. Horton, Director

Library of Congress Cataloging in Publication Data:

McKibbin, R. W. (Robert W.)

Slurry transport properties of graded coal waste.

(Report of investigations ; 8825)

Bibliography: p. 20.

Supt. of Docs. no.: I 28.23:8825.

1. Coal slurry. 2. Coal mine waste. I. Backer, R. R. (Ronald R.). II. Busch, R. A. (Richard A.). III. Title. IV. Series: Report of investigations (United States. Bureau of Mines) ; 8825.

TN23.U43 [TN817] 622s [662.6'23] 83-14484

CONTENTS



ILLUSTRATIONS



TABLES

## UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

| | | | |
|---|---|---|---|
| °C | degree Celsius | mm | millimeter |
| cu ft | cubic foot | min | minute |
| cu in | cubic inch | pct | percent |
| fps | foot per second | pH | negative logarithm of the hydrogen-ion concentration |
| ft | foot | psi | pound per square inch |
| gal | gallon | rpm | revolution per minute |
| gpm | gallon per minute | sec | second |
| hp | horsepower | tpd | ton per day |
| hr | hour | tph | ton per hour |
| in | inch | wt-pct | weight-percent |
| kw | kilowatt | | |
| lb | pound | | |

# SLURRY TRANSPORT PROPERTIES OF GRADED COAL WASTE

By R. W. McKibbin,[1] R. R. Backer,[2] and R. A. Busch[3]

ABSTRACT

The Bureau of Mines conducted laboratory tests to determine the slurry transport and deposition properties of coal waste. A 188.5-ft pipe test loop was constructed with instruments to measure density, flow, and power and discharge, suction, and differential pressures. A 20-ton sample of Western coal waste was crushed and screened to 100 pct minus 1/2 in. Eight loop tests using this graded waste were run at slurry densities ranging from 1.15 (25 wt-pct solids) to 1.46 (60 wt-pct solids). The resultant friction-pressure gradients ranged from 0.06 to 0.24 ft of water per foot of 4-in standard steel pipe. Particle-size degradation was significant. In a typical loop test lasting 25 min, the minus 200-mesh fraction increased from 19 pct to 34 pct. Deposition tests showed that without the use of a flocculant, the slurries would not dewater when left to stand for 1 week. With flocculant, additional water was released; however, the settled slurries remained thixotropic. Further testing is necessary to determine their suitability for use as backfill material in active mines.

[1]Mining engineer.
[2]Supervisory mining engineer.
[3]Research civil engineer.
Spokane Research Center, Bureau of Mines, Spokane, WA.

# INTRODUCTION

The basic nature of the energy problem in the United States is undue dependence on imported oil. One approach to reducing this dependence is utilization of U.S. coal reserves, now set at about 228 billion tons or 29 pct of the world total. In 1980, U.S. miners produced 832 million tons of coal, 41 pct from underground mines found mostly east of the Mississippi and the remainder from surface mines. It is estimated that over 1.4 billion tons will be produced by the year 1990 (9).[4]

Fifty years ago, the benefication of raw coal was generally a simple and cheap process. Hand-loading produced a coarse product relatively free of impurities and suitable for consumption without further benefication. However, with the advent of conventional mining and, later, continuous mining, increased amounts of extraneous material--coal wastes--are being extracted along with the coal. Because of environmental regulations requiring clean coal, operators are facing a growing volume of wastes produced in cleaning operations. Approximately 28 pct of the material extracted from underground coal mines in the United States is rejected as coal waste.

The most common disposal method is surface impoundment, if space is available. Traditionally, dams were built of coarse waste, and fine waste was pumped behind the dam at very low operating costs; but recent evaluations have indicated that many such structures could be critically unsafe during periods of heavy rains. As a consequence, State and Federal regulations now govern the construction and abandonment of impoundments, and foundation and reclamation requirements are strict. The resulting expense associated with subsurface drainage systems, elaborate spillways, monitoring equipment, etc. has driven the average cost (1982) of impoundments to over $3.00 per ton of waste disposed.

Faced with these higher disposal costs, operators are now looking for alternative coal waste disposal methods. One method being examined is backfilling in active underground mines. In the past, underground disposal has been used in the anthracite region of Pennsylvania to control mine fires and surface subsidence. The Europeans and Soviets also use the concept of backfilling, particularly for thick, deep, steep, or multiple seams, and for working under cities and urbanized areas (5). In the United States, the practice of backfilling coal wastes in active coal mines has long been ignored for economic reasons. As long as it is significantly cheaper to dispose of mine wastes on the surface, there will be little incentive for the mine operator to return coal wastes underground. However, conditions are changing. In light of the trend toward increasing regulatory restraints, shortage of suitable terrain for constructing impoundments, and the projected demand for increased coal production, the economic feasibility of underground disposal of coal mining wastes is likely to increase.

The Bureau of Mines has been active in mine waste disposal research for over 20 years. The general overall goals of this research are (1) to define and assess the major structural stability and environmental problems associated with the disposal of mine and mill wastes for various commodities, (2) to design and develop control techniques addressing these problems and promote their incorporation into industry practice, and (3) to develop alternative disposal practices promoting effective land use and waste utilization. As part of its program in mine waste disposal technology (8), the Bureau initiated projects to examine the feasibility of using coal waste as mine backfill material. One of these projects, seeking an improved hydraulic method for coal

[4]Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.

waste disposal, investigated the slurry transport and deposition properties of coal waste. The results are reported here.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to the Powderhorn Coal Co., Palisade, CO, especially Dale L. Fenwick, assistant general manager, for their cooperation and assistance in collection and shipment of the coal waste material used in this study.

## PIPE TEST LOOP

### DESIGN

A pipe test loop may be defined as a short, closed-circuit pipeline, with instrumentation and controls. Such test loops are essential for generating the engineering data needed for a full-scale pipeline design. Pressure loss per unit length of pipe, minimum operating velocity, shutdown and restart capabilities, and power consumption can be determined.

The Bureau of Mines pipe test loop (fig. 1) was conceived as an apparatus for testing the feasibility of returning slurried coal waste underground. To this end, it was decided that the pump and pipe size should be approximately the same as would be used in a commercial application. In 1975, 388 coal cleaning plants produced 107,101,000 tons of waste (10). Assuming 300 days of operation per year, the average plant then produced 920 tpd of waste.

Since one of the project objectives was to determine the optimum slurry density and gradation, the pipe loop had to be

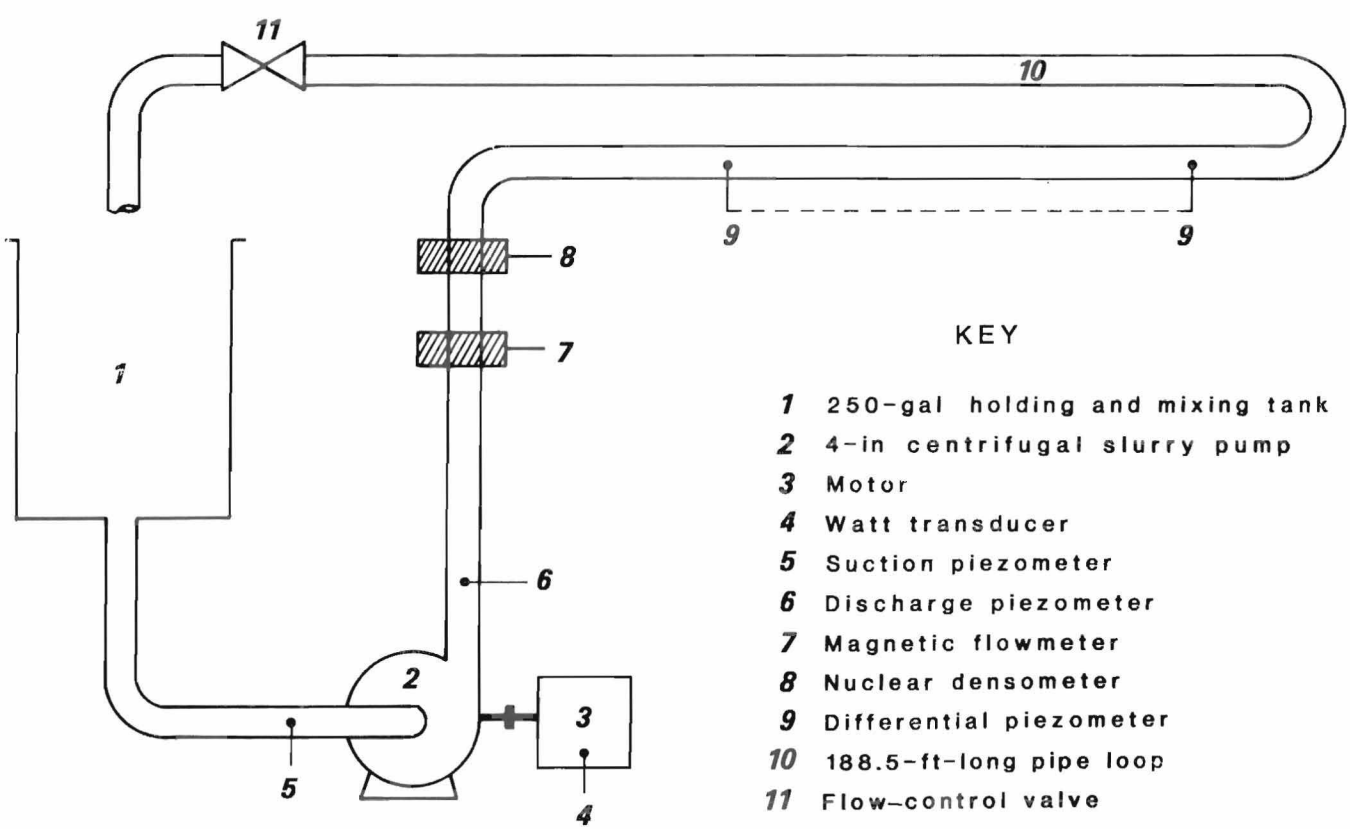


FIGURE 1. - Pipe test loop schematic.

designed for a wide range of densities. It was assumed that coal waste slurries of from 30 to 70 wt-pct solids might be tested, and that a backfill operation would operate 16 hr per day. For 920 tpd, the flow rates would range from 200 to 600 gpm (fig. 2).

Another project consideration was the critical carrying velocity of the slurries, which could range from about 6 to 10 fps. The relationship between flow and velocity for selected pipe sizes (table 1) shows that 4-in standard steel pipe gives the proper combinations of carrying velocity and quantity for the range of coal waste slurries to be encountered. Pipe loop specifications were thus set as follows: able to pump up to 600 gpm at up to 70 wt-pct coal waste solids (slurry specific gravity = 1.54) to a maximum head of 60 ft through a 4-in line.

## COMPONENTS

The pump selected for this application is a cast-iron centrifugal, equipped with a variable-speed (547- to 1,094-rpm) belt drive and 15-hp electric motor (fig. 3). The slurry pump draws material from a

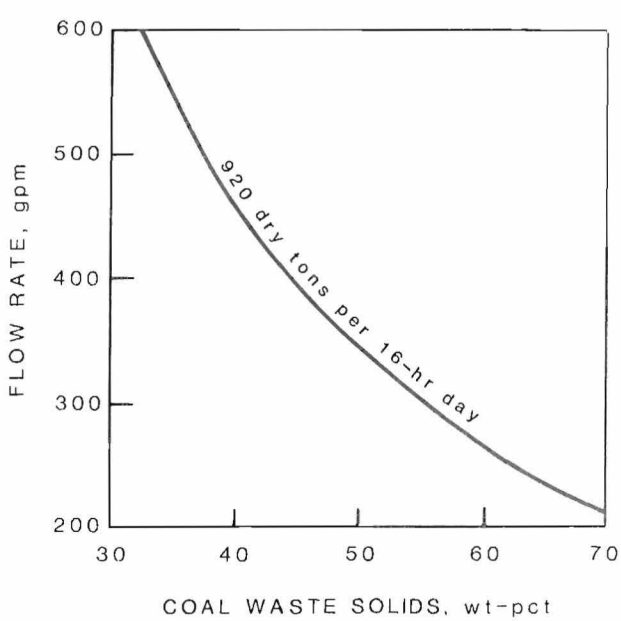


FIGURE 2. - Coal-waste mass-flow relationship. (Assume coal waste dry specific gravity = 2.10.)

TABLE 1 - Flow rate versus velocity for various standard pipe sizes

| Flow rate, gpm | Velocity, fps | | |
|---|---|---|---|
| | 3 in | 4 in | 6 in |
| 200..... | 8.70 | 5.03 | 2.24 |
| 300..... | 13.05 | 7.54 | 3.36 |
| 400..... | 17.40 | 10.05 | 4.48 |
| 500..... | 21.75 | 12.57 | 5.60 |
| 600..... | 26.10 | 15.08 | 6.72 |

250-gal tank (fig. 4) equipped with paddle mixing blades, pumps it through 188.5 ft (see appendix A) of standard 4-in pipe, and then discharges it back into the mixing tank. The principal flow-control device is a Clarkson Series C[5] pinch valve located just ahead of the discharge into the tank. This valve (fig. 5) contains a rubber sleeve compressed by hydraulic fluid, so that it always maintains a round and perfectly centered aperture. This type of valve is essential for velocity control of slurries containing large particles.

Pump and pipe loop performance is monitored continuously by means of six main instruments. Flow and specific gravity are measured with a magnetic flowmeter and a nuclear densimeter (fig. 6) installed in a vertical section. Combining data from these two devices yields the mass-flow rate. Pump suction and discharge pressures and pipeline differential pressure are measured through piezometers in the pipe (fig. 7). The pressure from the piezometers is transmitted to bellows-type electronic pressure transmitters (fig. 8) via nylon tubing. Gauges and a manometer serve as backup and calibration devices for the pressure transmitters. The pump motor power consumption is measured by a watt transducer. All six of these instruments generate signals that are fed to a bank of chart recorders, thus providing a continuous and permanent record of each pipe loop test.

[5]Reference to specific equipment, trade names, or manufacturers does not imply endorsement by the Bureau of Mines.

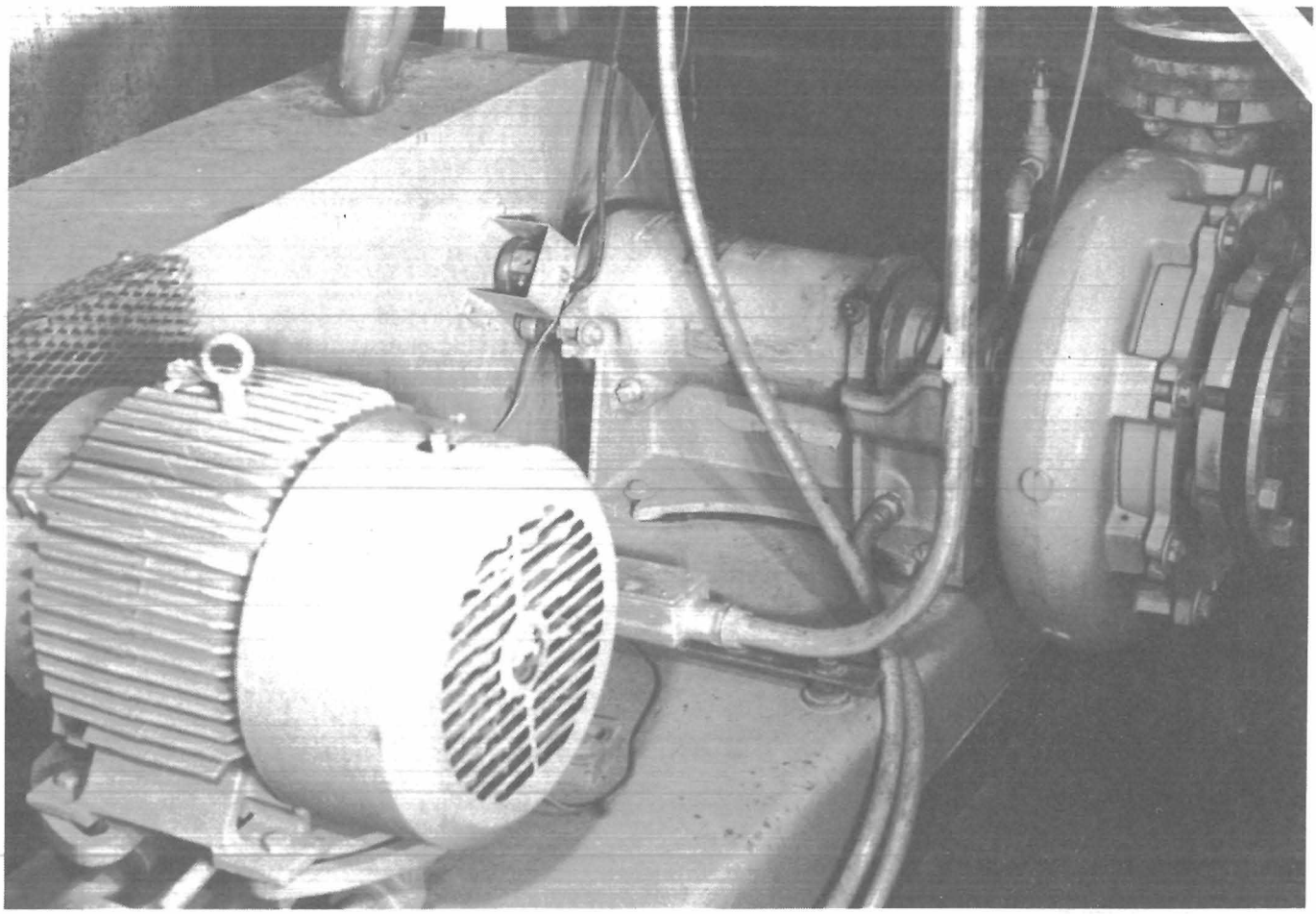

FIGURE 3. - Slurry pump with variable speed drive.

Additional components include various drain and discharge valves, air bleed valves, slurry-pump digital tachometer, digital thermometer in the holding tank, and a high-pressure boost pump. The boost pump supplies municipal water to the packing gland of the slurry pump and to the piezometer lines when flushing out sediment.

## SAMPLE DESCRIPTION

The Powderhorn Coal Co.'s Roadside Preparation Plant produces about 2,000 tpd of coal waste. The waste is transferred from the plant by belt conveyor to a surge pile where it is loaded by a front-end loader into trucks and then hauled to the disposal area.

In June 1981, a 20-ton bulk sample of Roadside waste was collected from the surge pile and trucked to the Bureau's Spokane (WA) Research Center. Upon arrival, the material was spread on a paved area and was periodically mixed and respread to aid drying. The waste was then reduced to 100 pct minus 1/2 in. in a small crushing and screening plant (fig. 9) and placed in steel drums for subsequent tests. After crushing, grab samples were collected from each of the drums. These were combined and resplit to produce one sample for physical property testing.

Physical property testing was performed using the following procedures:

1. Specific gravity was determined according to ASTM Standard D 854-58 (1).

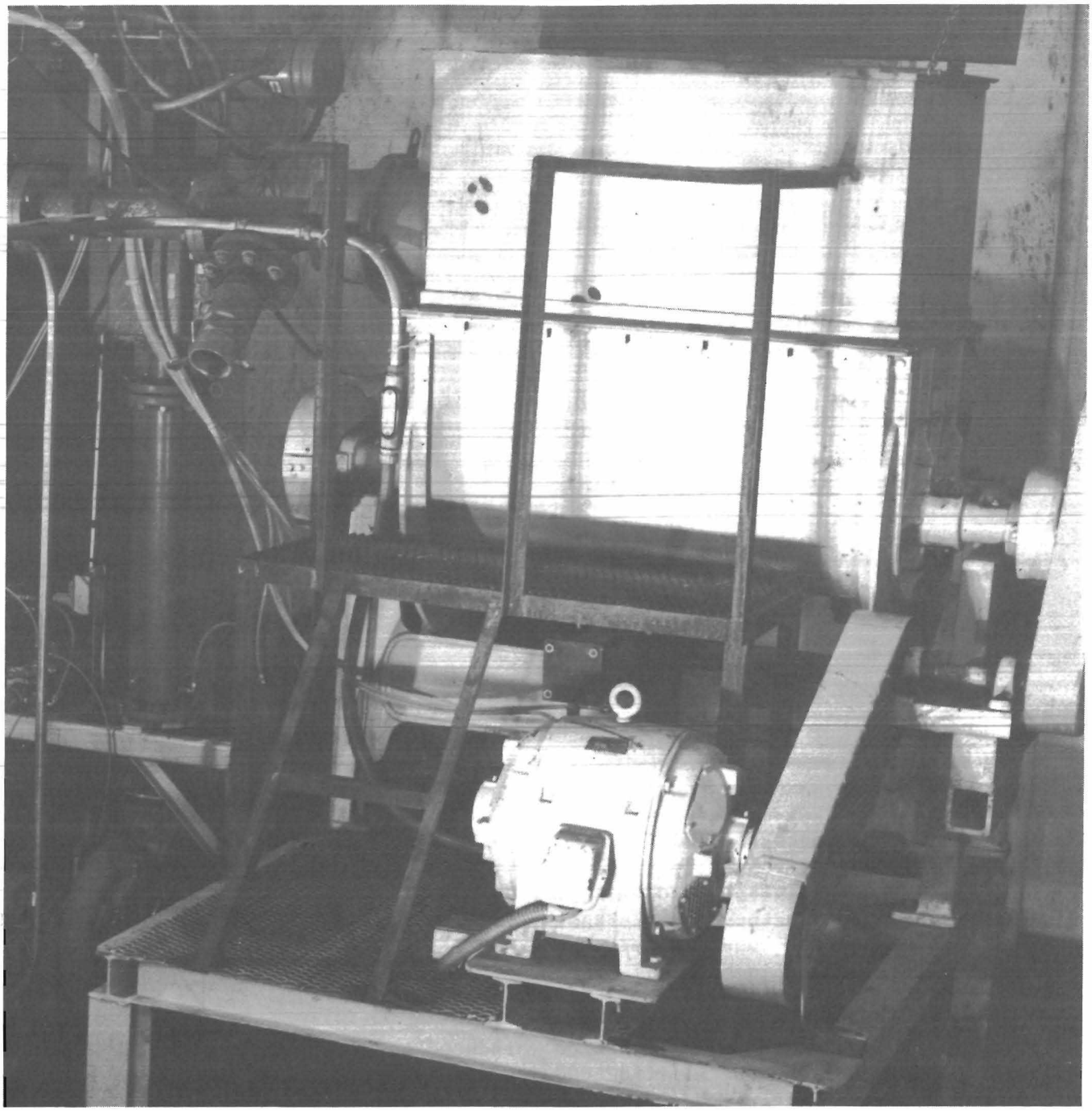

FIGURE 4. - Holding and mixing tank. Flow-control valve is at left of tank.

2. Particle-size analysis was performed according to ASTM Standard D 422-63, (2). The minus 200-mesh fraction was tested with a particle-size analyzer, operating on the principle of Stokes' law and utilizing X-ray absorption.

Test results yielded an average specific gravity of 2.10 for the graded waste. This value is typical of Western coal waste materials (4) and is used in all subsequent calculations. The particle-size analysis (fig. 10) is also typical and is used as a base for comparing particle-size degradation during and after the pipe loop tests.

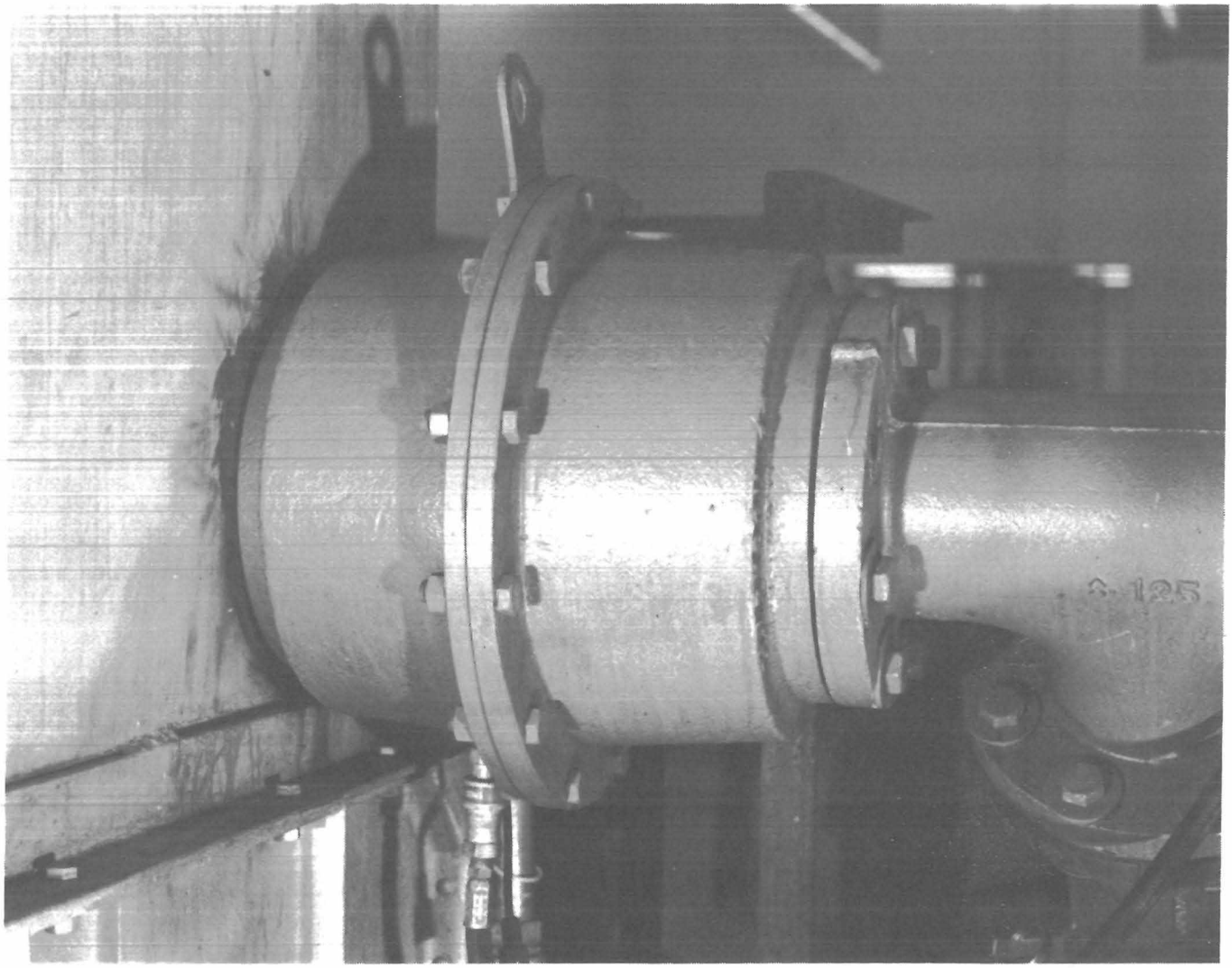

FIGURE 5. - Flow-control valve.

## SLURRY TESTS

### CALIBRATION PROCEDURE

Prior to any pipe loop test, the operation and calibration of each instrument are checked by running a short test using municipal water. Since the system is always flushed and purged after a loop test, the first step is to fill the holding tank with water. The main pump is turned on to fill the pipe loop with water, and additional makeup water is then added to the tank to fill the system to its 350-gal capacity.

The three-way valves (fig. 11) are turned from position 2 to position 1, which allows high-pressure water to flush entrapped air or sediments from the piezometer lines. At the same time, the gauge bleed valves are opened, thus returning the gauge and pressure transmitter readings to the ambient atmospheric pressure. The chart recorders can then be zeroed. The gauge bleed valves are closed and the three-way valves turned from position 1 to position 3. This places the gauges and transmitters on-line, and the chart recorder indications are compared to the respective gauges or manometer.

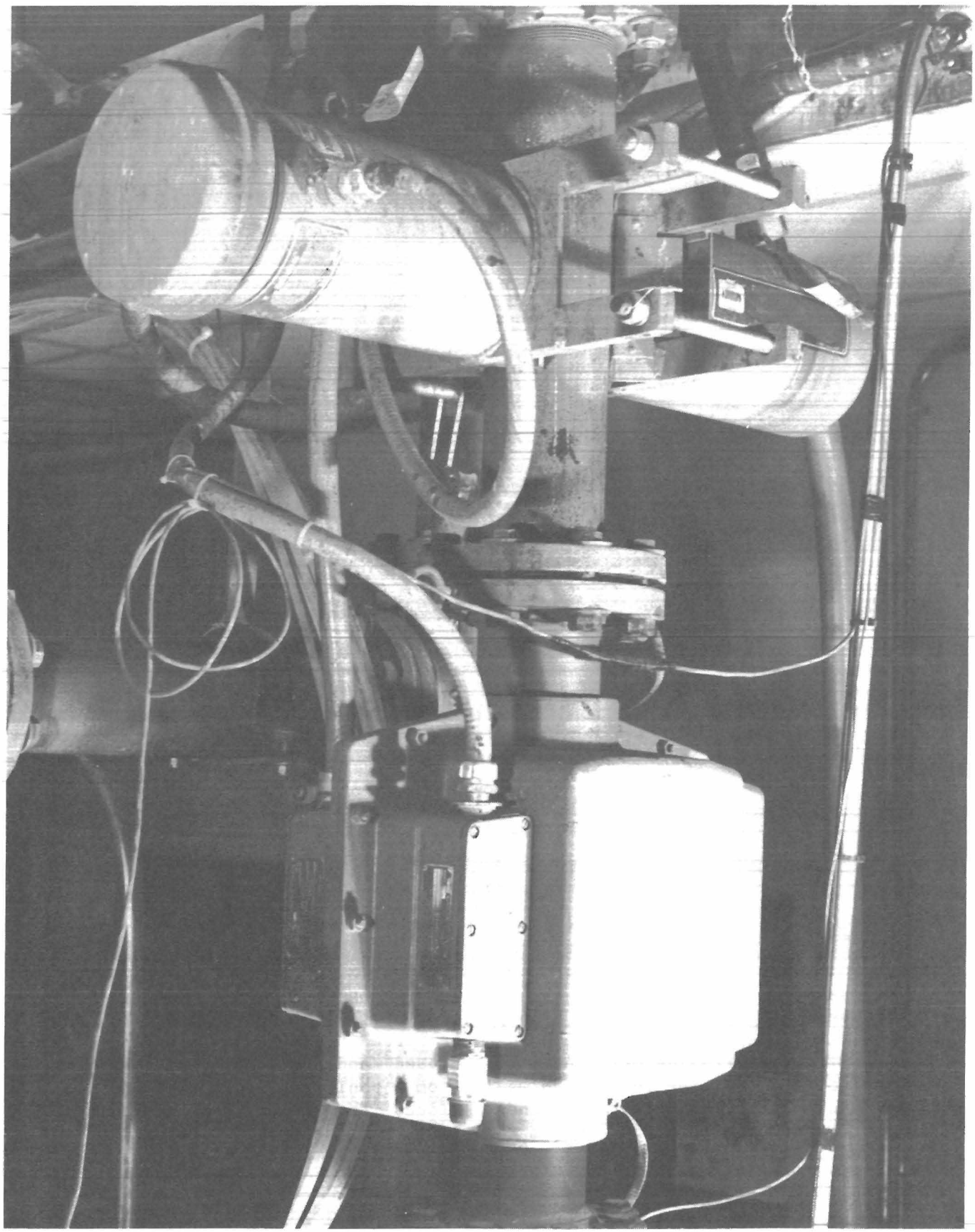

FIGURE 6. -- Magnetic flowmeter (bottom) and nuclear densimeter (top).

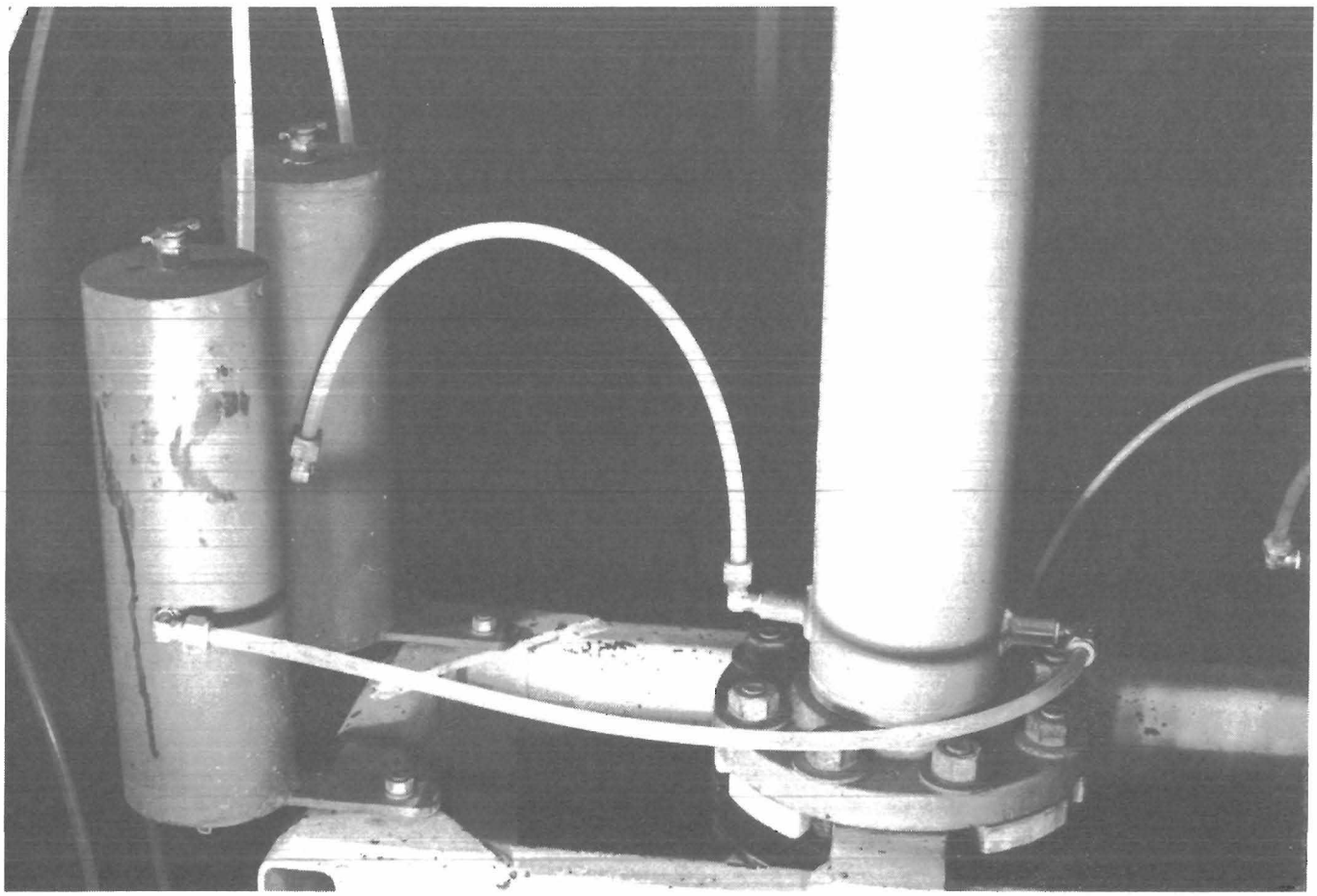

FIGURE 7. - Discharge pressure piezometers (right) and sediment pots (left).

The digital tachometer and thermometer are checked by a handheld mechanical tachometer and mercury thermometer, and the nuclear densimeter chart recorder is set at 1.000. Finally, the main pump is turned off and the wattmeter and flowmeter chart recorders are zeroed.

In order to insure the quality of data, periodic maintenance checks are performed. The full-scale indications, or spans, of the various instruments are periodically checked according to the factory-prescribed maintenance schedules. Pressure transmitters are disconnected and then compared against master test gauges. The flowmeter is checked by measuring the time required to pump a known volume of water. The densimeter and wattmeter spans are set by following factory-prescribed procedures.

## LOOP TEST PROCEDURE

Loop tests, using the graded minus 1/2-in coal waste, were conducted at eight different slurry densities. As mentioned, a short calibration test using municipal water is run before each slurry test. This leaves both the mixing tank and pipe loop full of water. Experience shows the preferred method for mixing the slurry is to draw off the requisite amount of water, turn the pump on, and gradually add the specified amount of dry waste (fig. 12) to the remaining circulating water. The matrix for the eight tests is given in table 2.

The flow-control valve remains open while the waste is added, and the three-way gauge valves are in the off (2)

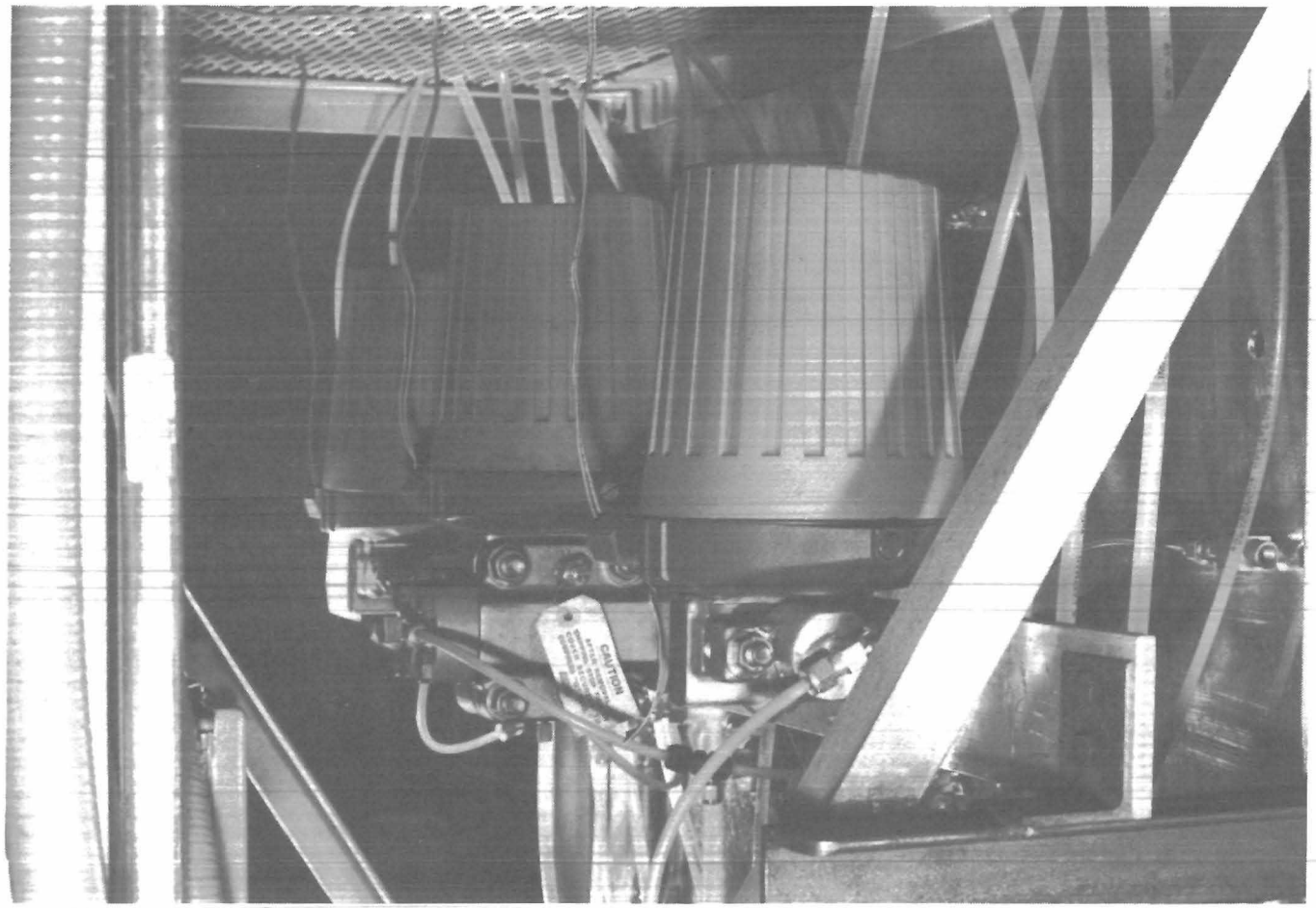


FIGURE 8. - Electronic pressure transmitters.

TABLE 2. - Slurry test matrix

| Coal waste solids, wt-pct | To make 350 gal of slurry-- | |
|---|---|---|
| | Dry weight of solids, lb | Volume of water, gal |
| 25..... | 840 | 302 |
| 30..... | 1,039 | 291 |
| 35..... | 1,251 | 278 |
| 40..... | 1,477 | 266 |
| 45..... | 1,718 | 252 |
| 50..... | 1,978 | 247 |
| 55..... | 2,256 | 231 |
| 60..... | 2,554 | 204 |

position. Although an exact weight-percent solids level cannot be achieved, a good approximation can be obtained by preweighing the dried waste and closely monitoring the nuclear densimeter as the waste is added. Once the desired weight-percent solids level is reached, the material is allowed to circulate at full flow until the density reading stabilizes (usually within 2 min).

When the density stabilizes, the three-way valves are turned to position 1 for about 15 sec to insure clear lines, then to position 3 (fig. 13). With all instruments now on-line, a series of readings is taken. Discharge, suction, and differential pressures, flow, density, and power are chart-recorded. Pump revolutions per minute and slurry temperature, as well as the gauge and manometer readings, are recorded manually. The three-way valves are then turned off.

After the first series of readings, the slurry's flow is throttled by partially closing the flow-control valve, the instruments are allowed to stabilize again, and the reading procedure is repeated. In such a manner, from 8 to 10 readings

FIGURE 9. - Crushing and screening plant.

can be obtained before the critical carrying velocity is reached, as evidenced by a rapid drop in the slurry density. With a further reduction in flow, there is a risk that the pipe loop's vertical sections will become plugged, particularly when pumping slurries with over 20 wt-pct solids.

Once these data are recorded, the flow-control valve is opened, allowing the slurry to return to full flow conditions. When the instruments have stabilized, a sample of the circulating slurry is collected for grain-size analysis. This completes the loop test. The actual data for the eight tests and the data for a typical clear water test, as taken from the chart recordings, are tabulated in appendix B. If settling tests are to be run, they are started promptly in order to minimize particle-size degradation.

## LOOP TEST RESULTS

### Friction Loss

From the standpoint of scaleup for an actual underground backfill system, differential pressure ($P_{diff}$) and flow are the most important data to be recorded. From these, the friction-pressure gradient may be determined. This, in turn, allows the engineer to project pump and power requirements for the full-scale system.

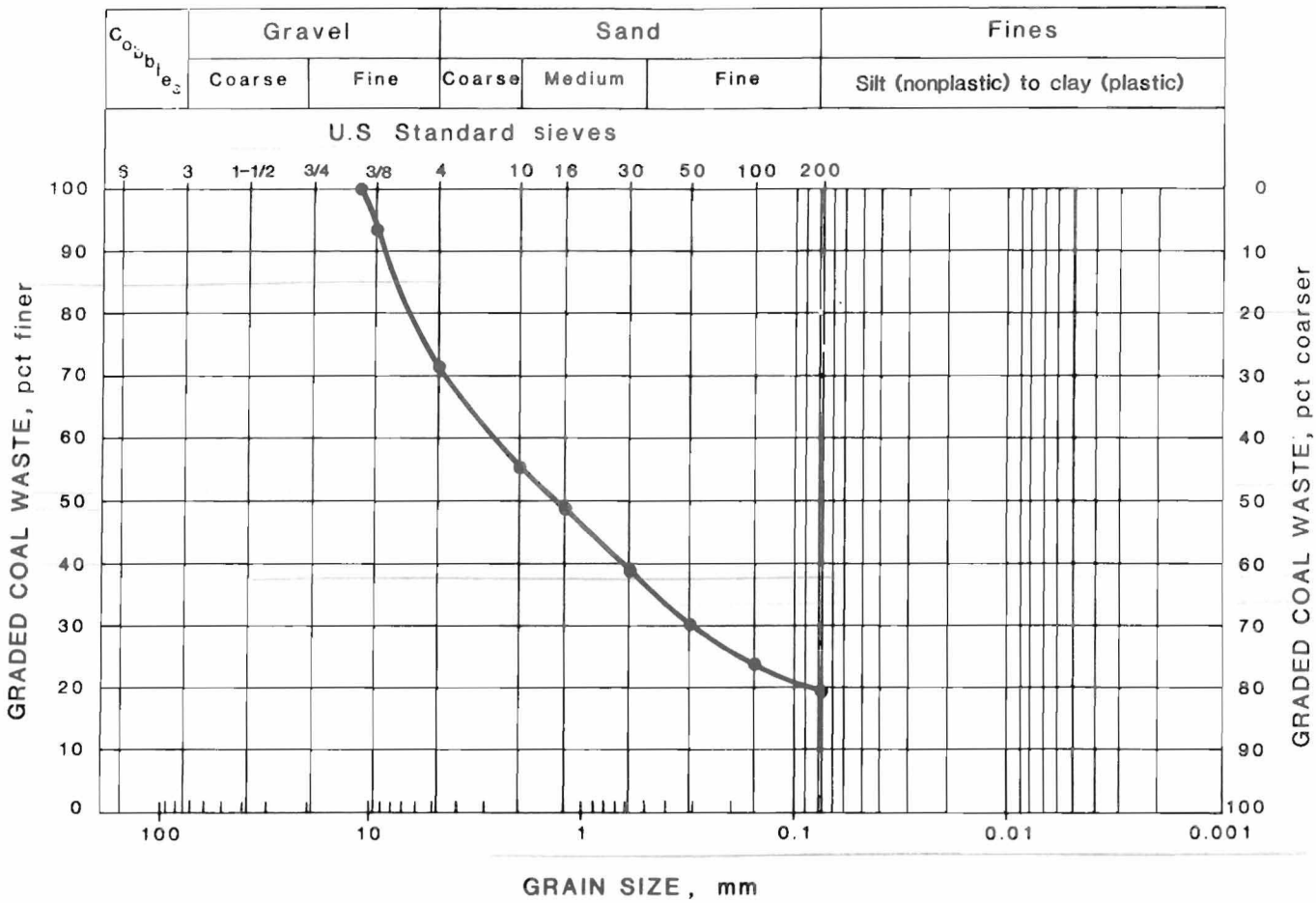


FIGURE 10. - Particle-size distribution, graded waste.

Differential pressure is measured by two piezometers located 50.48 ft apart in a straight and level section of the pipe loop. The piezometers are preceded and followed by at least 6 ft more of straight pipe, in order to minimize any effects on the slurry's flow by elbows or other restrictions. Since the conventional units for friction-pressure gradient ($H_f$) are feet of water per foot of pipe, the chart recorder indication ($P_{diff}$) in pounds per square inch is converted according to:

$$H_f = P_{diff} \left(\frac{1{,}728 \text{ cu in}}{\text{cu ft}}\right) \left(\frac{\text{ft}}{12 \text{ in}}\right) \left(\frac{\text{cu ft of water}}{62.41 \text{ lb}}\right) \left(\frac{1}{50.48 \text{ ft of pipe}}\right)$$

$$= P_{diff} \ (0.046).$$

Flow in gallons per minute is converted to velocity (V) in feet per second by:

$$V = \text{flow} \left(\frac{\text{min}}{60 \text{ sec}}\right) \left(\frac{\text{lineal ft of 4-in standard pipe}}{0.6613 \text{ gal}}\right) = \text{flow } (0.0252).$$

Once this was done for each of the eight slurry tests and the clear water test, the ordered pairs (V, $H_f$) were subjected to a least squares fit analysis (7). Although a rather small number of data points are present--a constraint on fitting a mathematical model with several parameters--the shape of the data implies something other than the usual straight line fit. A second-order polynomial

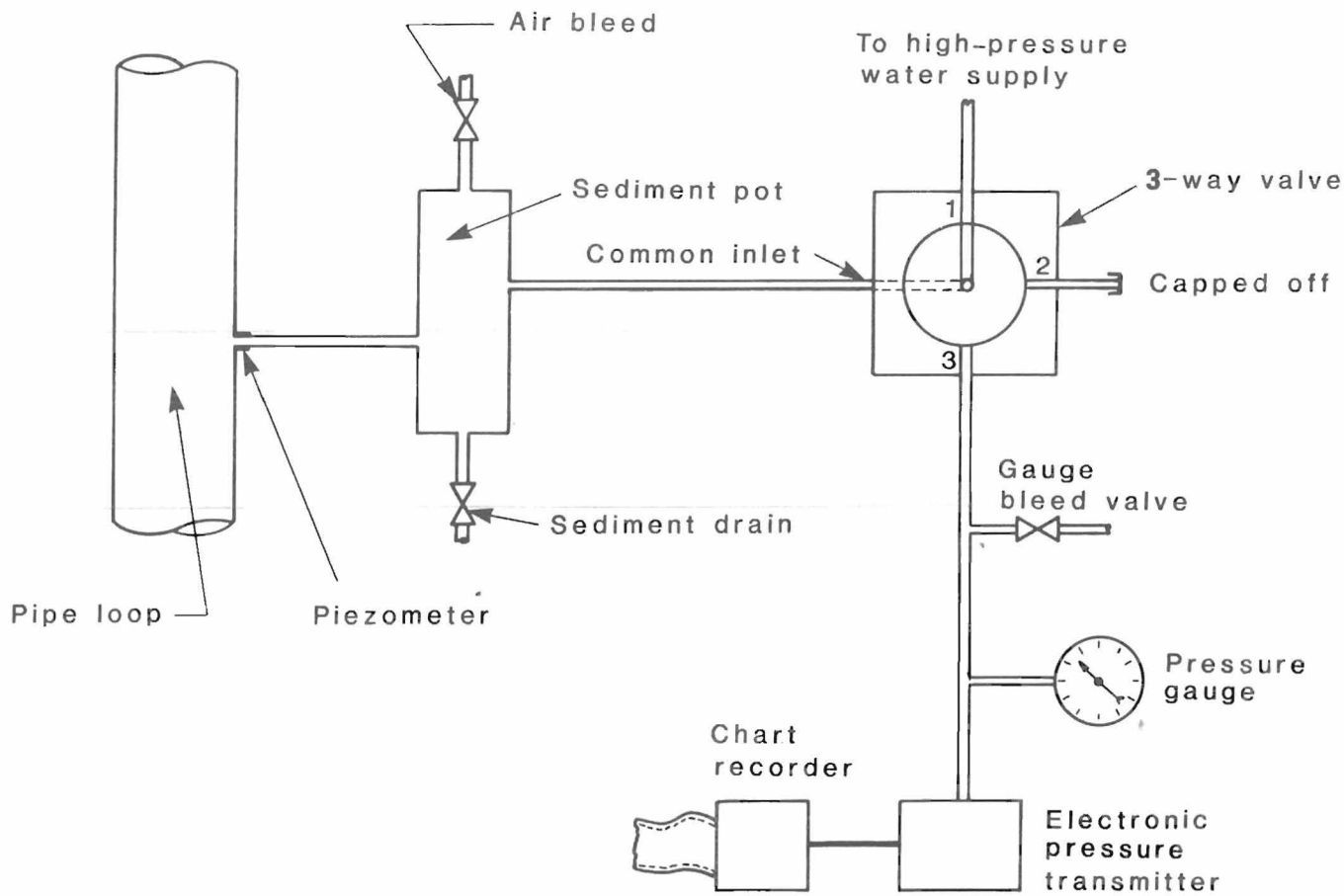


FIGURE 11. - Typical gauge plumbing schematic.

(parabola) seems to provide an adequate representation of the data; the only anomaly is the "reverse concavity" of the 40-pct data. The polynomial equations[6] were then used in graphing the friction-pressure gradient versus velocity (fig. 14). It must be kept in mind that the friction-loss data may be low compared with data from a continuous feed installation owing to the very low inventory of slurry (1 to 2 min). The heterogeneous component of friction losses would be very significant in a system with a continuous supply of new feed, whereas it may be mostly unobserved in the low inventory system. Note also that these curves are valid for projecting friction loss *only* in 4-in standard pipe.

[6]The actual polynomial fuctions are tabulated in appendix C.

## Particle-Size Degradation

After crushing and screening of the coal waste to 100 pct minus 1/2 in, grab samples were collected from each storage drum, combined, and resplit. The particle-size distribution of this graded material is shown in figure 10. Following each loop test, a sample of the coal waste surry was collected at the point of discharge into the settling tank. This sample was then dried and screened. The average elapsed time between the addition of the graded waste to the circulating water and collection of the slurry sample was 26 min.

When the particle-size distribution of the sample is compared against the original distribution curve (fig. 15), the degradation becomes evident, particularly

FIGURE 12. - Adding dry waste to slurry mixing tank.

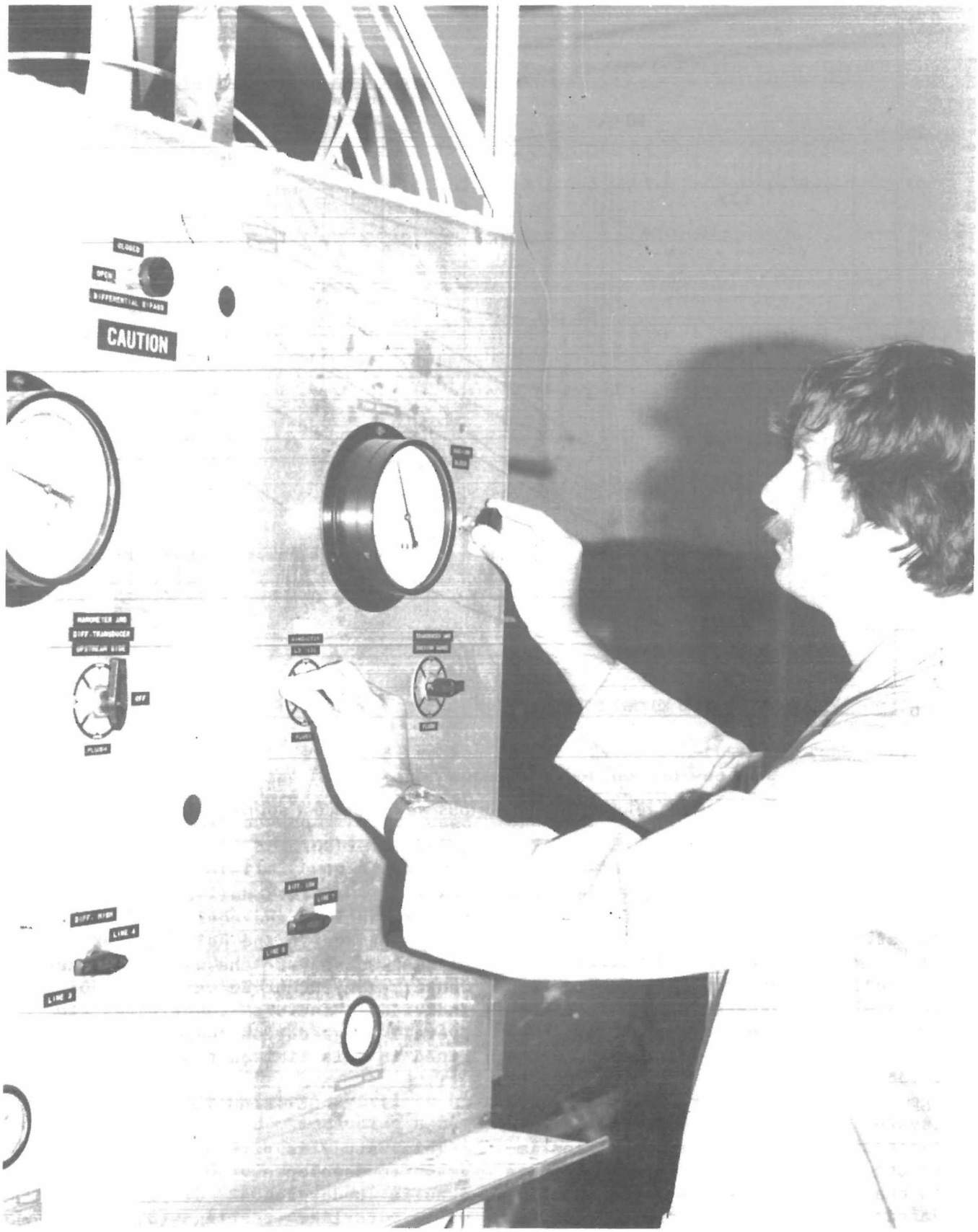


FIGURE 13. Operating three-way gauge valves.

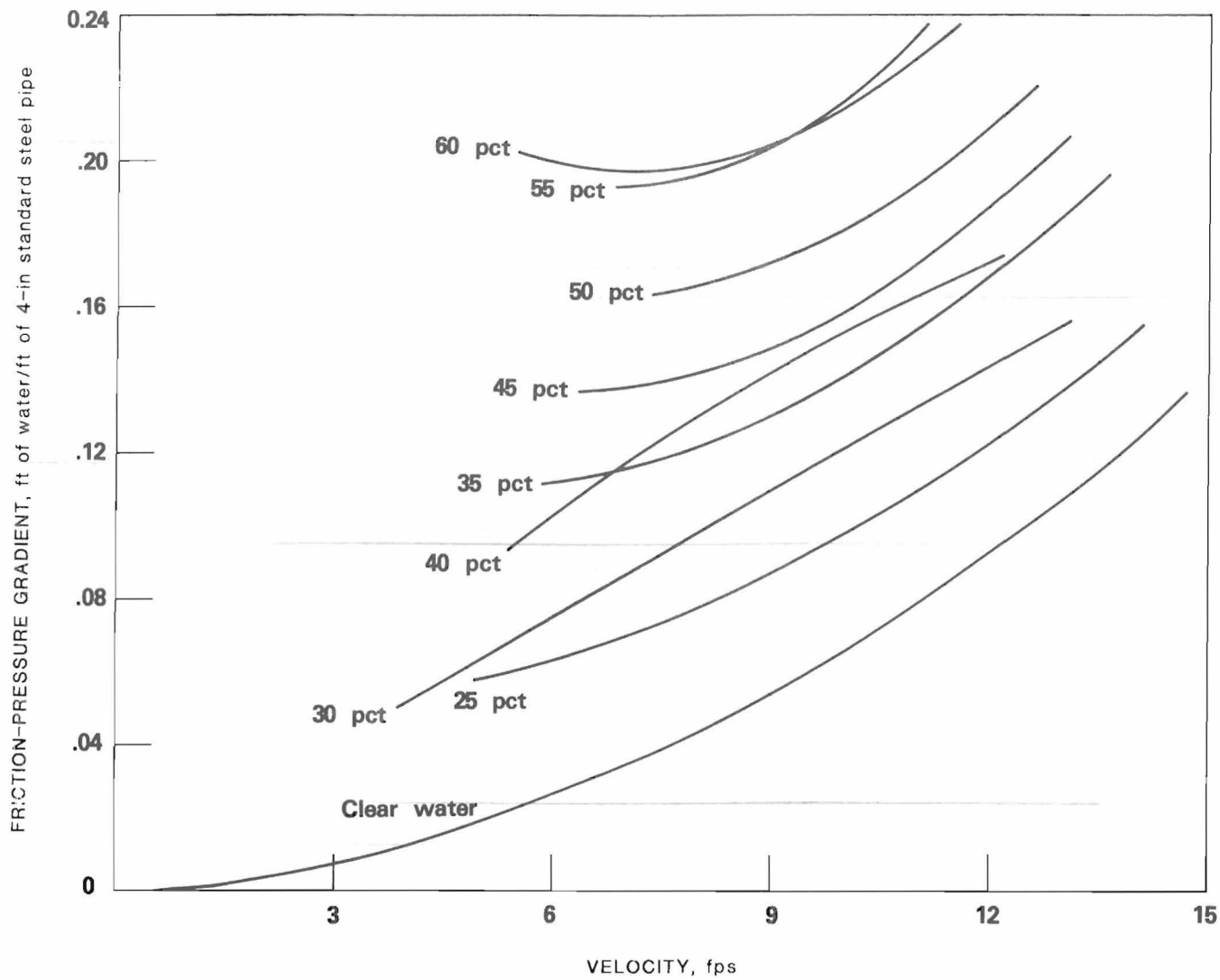


FIGURE 14. - Friction-loss relationship for various weight-percent solids coal waste slurries and clear water.

in the smaller size ranges. The minus 200-mesh fraction increased from 19 pct to 34 pct.

The specific cause of the degradation is difficult to ascertain and is likely due to a combination of factors. With an average residence time of 26 min in the test loop, at an average pumping rate of 470 gpm, the slurry circulates through the system approximately 35 times. During each circuit the slurry particles impact the pump impeller and undergo a rapid change in momentum, contributing to their breakdown. After 35 circuits through the loop, the slurry has actually traveled 5,400 ft and been subject to the resultant frictional stresses. Other factors include the action of the paddle mixing blades in the holding tank and the slaking action of the water on the coal waste. The extent to which each of these individual factors contributes to the overall degradation could not be determined in this limited testing.

## SETTLING TESTS

This study is part of an overall program to develop a viable method for hydraulic underground disposal of coal waste. Earlier testing (3, 6) on selected samples showed that most coal wastes contain significant proportions of

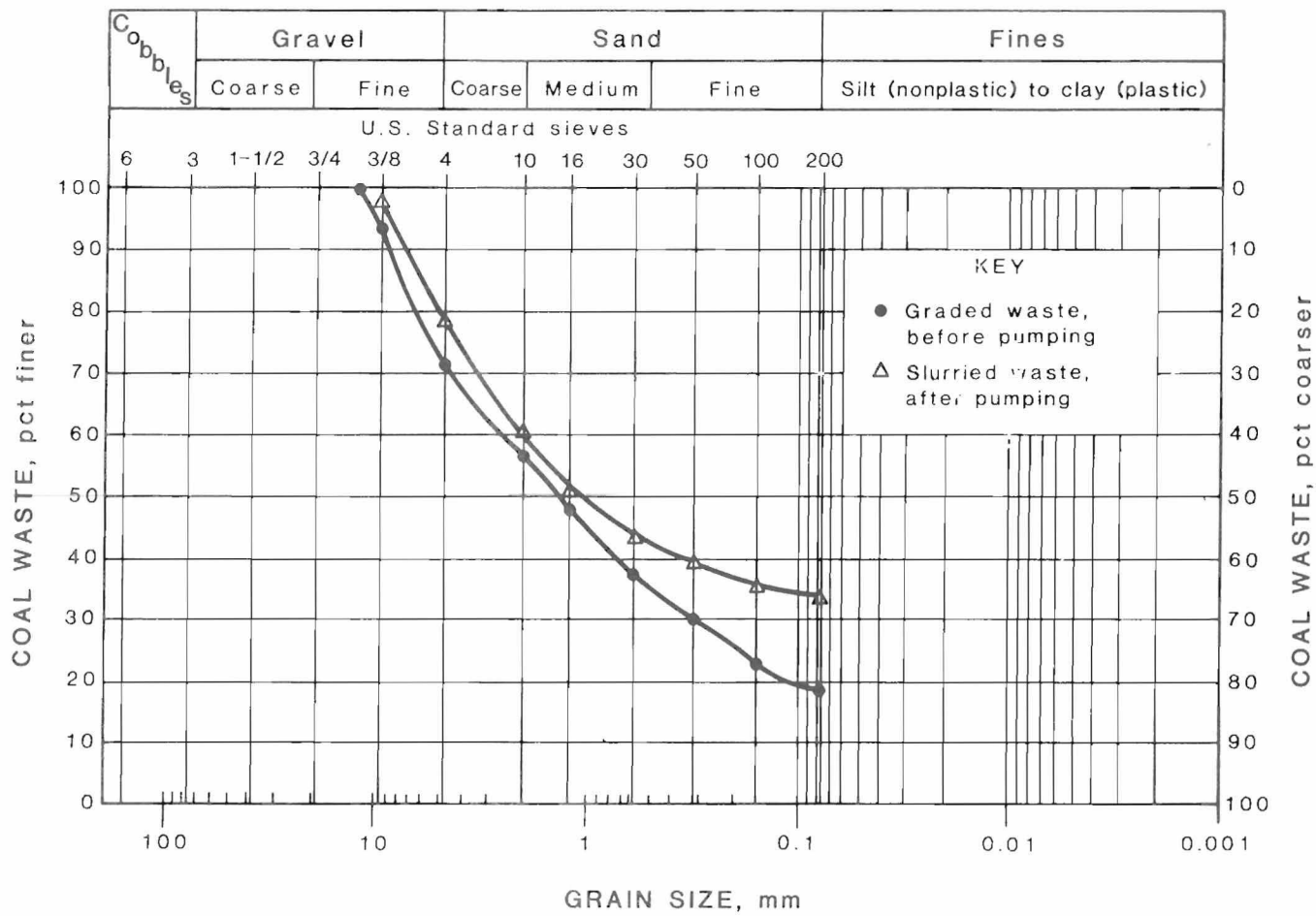


FIGURE 15. - Particle-size distribution, graded versus slurried waste.

minus 200-mesh material and tend to be thixotropic in nature and difficult to dewater. It is considered desirable, if not essential, that any coal waste used as hydraulic backfill be capable of being dewatered. Such material would exhibit improved structural support characteristics, allow recirculation of the transport water and occupy less space, and would not be subject to catastrophic release into active mine workings. Since the coal waste used in this study was 19 pct minus 200 mesh, a dewatering problem was anticipated.

To address this problem, several techniques were considered, including horizontal blanket sand drains, vertical wicks of porous fabric, porous bulkheads, deposition of the slurried waste on a slope, the use of flocculants, and various combinations of these methods. The methods were tested by constructing a 2- by 2- by 40-ft-long tank (fig. 16) with bottom and end drains. The slope of the tank could be varied by blocking up one end.

Following each loop test, the coal waste slurry was discharged into one end of the tank. Since the weight-percent solids varied with each loop test, it was not possible to try each dewatering technique at several different solids levels. However, the following tank and drain configurations were tested:

1. Tank, level; bottom drains at 10-ft intervals.

2. Tank, level; 2-in horizontal sand layer on bottom of tank; bottom drains.

3. Tank, 2-pct slope; porous bulkhead at far end; end drain.

FIGURE 16. - Settling tank.

4. Tank, 2-pct slope; bulkhead; 2-in sand layer; bottom and end drains.

5. Tank, 2-pct slope; vertical fabric wicks; bulkhead; end drain.

6. Tank, level; addition of flocculant at point of discharge into tank; bottom drains.

7. Tank, 3-pct slope; flocculant; bulkhead; end drain.

8. Tank, 3-pct slope; flocculant; bulkhead; 2-in sand layer; bottom and end drains.

Each change in the tank configuration was an attempt to improve the drainage characteristics of the coal waste slurry.

Results indicate that without the use of flocculant (tank configurations 1 through 5), the material would not dewater when left to stand for 1 week. It is believed that blinding of the sand drains and porous fabric by minus 200-mesh material prevented migration of the water.

In the tests using flocculant, a modified procedure was used. Prior to the loop test, a 10-gal batch of 1 pct Cyanamid Superfloc 1202 was prepared. This anionic flocculant was then kept circulating in a small drum by means of a gear pump. Following the loop test, lime was added to the circulating slurry at the rate of 2 wt-pct of dry coal waste solids, to raise the pH of the material to approximately 10. After 5 min were allowed for the lime to mix, the slurry was discharged into a mixing well at the end of the 40-ft tank. The previously diluted flocculant was introduced at this point also, at the rate of 0.1 wt-pct of dry coal waste solids. As soon as the two streams contacted each other, well-defined flocs of coal waste were produced. These flowed over a weir into the main portion of the tank.

Results of the settling tests using flocculant indicate that up to 30 pct of the water was released after the flocculant was added to the coal waste slurry. This water quickly drained over the surface and through the bulkhead (tank configurations 7 and 8). The remaining waste was thixotropic, however, and could not be tested for shear strength. It would not provide structural support to mine workings if used as backfill. Further testing, to include pH conditioning, flocculant type and dose, and mixing methods, could refine this dewatering technique to the point that the coal waste would be suitable for mine backfill. Such a test program is currently in progress at the Bureau's Tuscaloosa (AL) Research Center (11).

## CONCLUSIONS

The results of the investigation as reported here are based on a limited test program using only one sample of a Western coal waste. Wastes from other sources, which would vary in clay content, particle-size distribution, mineralogy, etc., would likely exhibit different slurry transport and deposition properties. The data were obtained while significant degradation was occurring, which more than likely affected the friction loss and settling test results. In commercial systems, the slurry will pass through the pumping system only once, so the recirculating test loop data can give misleading results. Note also that the friction-pressure gradient data are based on 4-in standard steel pipe, and that figures for other pipe sizes would vary. With these restraints in mind, the following conclusions may be drawn:

1. Coal waste slurries containing 25 to 60 wt-pct solids may be pumped using conventional pipe systems.

2. Particle-size degradation during pumping is significant and is a contributing factor to the poor dewatering characteristics of the deposited slurry.

3. None of the slurries tested would dewater without the use of flocculant. With flocculant, additional water was released as the slurry was deposited, but the slurry remained thixotropic.

4. Refinement of the test procedure would make the system more representative of a commercial operation. This would include limiting the amount of recirculation of slurry, determining deposition of coarse solids and slip in the loop (especially at low velocities), shutdown and restart testing, calibrating instruments on slurry, recalibrating the system (including pipe roughness) directly after testing, and not drying the solids and then reslurrying.

5. Additional testing, using samples of coal waste from other mines and geographic regions, is necessary to confirm the slurry transport data generated in this work.

6. Further work needs to be done on the placement of slurried coal waste. This could include refining of flocculant use and incorporation of mechanical dewatering aids.

## REFERENCES


1. American Society for Testing and Materials. Standard Test Method for Specific Gravity of Soils. D 854-58 in 1982 Annual Book of ASTM Standards: Part 19, Natural Building Stones; Soil and Rock. Philadelphia, PA, 1982, pp. 212-214.

2. _____. Standard Method for Particle-Size Analysis of Soils. D 422-63 in 1982 Annual Book of ASTM Standards: Part 19, Natural Building Stones; Soil and Rock. Philadephia, PA, 1982, pp. 112-122.

3. Backer, R. R., and R. A. Busch. Fine Coal-Refuse Slurry Dewatering. BuMines RI 8581, 1981, 18 pp.

4. Backer, R. R., R. A. Busch, and L. A. Atkins. Physical Properties of Western Coal Waste Materials. BuMines RI 8216, 1977, 29 pp.

5. Brauner, G. Subsidence Due to Underground Mining. BuMines IC 8572, 1973, 53 pp.

6. Jacobsen, S. P., W. Roushey, and E. L. Rau. Coal Waste Dewatering Systems (contract J0205012, CO School Mines Res. Inst.), BuMines OFR 114-81, 1981, 145 pp.; NTIS PB 81-244501.

7. McWilliams, P. C., and D. R. Tesarik. Multivariate Analysis Techniques With Application in Mining. BuMines IC 8782, 1978, 40 pp.

8. U.S. Bureau of Mines. Mine Waste Disposal Technology. Proceedings: Bureau of Mines Technology Transfer Workshop, Denver, Colo., July 16, 1981. BuMines IC 8857, 1981, 70 pp.

9. U.S. Energy Information Administration (Dep. Energy). Annual Report to Congress. V. 3, 1980, p. 97.

10. Westerstrom, L. W., and R. E. Harris. Coal-Bituminous and Lignite. Ch. in BuMines Minerals Yearbook 1975, v. 1, p. 435.

11. Zatko, J. R., B. J. Scheiner, and A. G. Smelley. Preliminary Studies on the Dewatering of Coal-Clay Waste Slurries Using a Flocculant. BuMines RI 8636, 1982, 15 pp.

## APPENDIX A.--EFFECTIVE LENGTH TEST

The actual length of the pipe loop is 153.25 ft. However, the pipe loop contains three 90° elbows and two tees. Although empirical methods exist for transposing the elbows and tees to equivalent lengths of straight pipe, it was decided to determine the effective length experimentally.

The actual procedure is quite simple. Two switching valves are placed in the differential pressure lines, one of which can be turned to either the differential high side or the pump discharge piezometers, the other to the differential low side or a special piezometer located just ahead of the mixing tank. Using clear water at 20° C, the head loss is measured first across the normal differential piezometers. The switching valves are then turned to the pump and tank discharge piezometers, and head loss is measured again. This procedure is repeated at several flow rates, and the ratios between the two measurements are averaged. The average is then multiplied by the known differential distance, thus giving the total effective length of the pipe loop. For the test loop, this figure is 188.5 ft. Data and calculations are shown in table A-1.

TABLE A-1.--Total effective length data

| Reading | Head loss, psi | | Head loss ratio,[1] HI/LO |
|---|---|---|---|
| | Across 50.48-ft straight section (LO) | Across total loop (HI) | |
| 1 | 2.04 | 7.50 | 3.68 |
| 2 | 1.66 | 6.06 | 3.65 |
| 3 | 1.29 | 4.63 | 3.59 |
| 4 | .95 | 3.43 | 3.61 |
| 5 | .68 | 2.40 | 3.53 |
| 6 | .69 | 2.45 | 3.55 |
| 7 | .83 | 3.04 | 3.66 |
| 8 | .98 | 3.64 | 3.71 |
| 9 | 1.19 | 4.32 | 3.63 |
| 10 | 1.45 | 5.37 | 3.70 |
| 11 | 1.74 | 6.44 | 3.70 |
| 12 | 2.00 | 7.36 | 3.68 |
| 13 | 2.23 | 8.25 | 3.70 |

[1]Average ratio is 3.65:

3.65 (50.48 ft) = 184.25 ft effective length between piezometers.
1.21 ft between pump and piezometer.
3.04 ft between tank and piezometer.
188.50 ft.

## APPENDIX B.--COAL WASTE SLURRY AND CLEAR WATER TEST DATA

The following tables contain data from the eight slurry tests and a typical clear water calibration test. Flow, specific gravity (sp gr), power consumption, and the three pressures--discharge ($P_d$), suction ($P_s$), and differential ($P_{diff}$)--represent the actual chart recording indications in inches multiplied by the appropriate chart scaling factor. Velocity, weight-percent solids, head loss, and dry tons per hour are then calculated from these basic data.

TABLE B-1. - Slurry test data

| Reading | Time,[1] min:sec | Flow, gpm | Velocity, fps | Sp gr | Solids, wt-pct | $P_d$, psi | $P_s$, psi | $P_{diff}$,[2] psi | Head loss[3] | Waste, dry tph | Power, kw |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SLURRY TEST 1--25 wt-pct (NOMINAL) SOLIDS | | | | | | | | | | | |
| 1 | 10:45 | 544 | 13.71 | 1.16 | 26.3 | 18.6 | 1.5 | 3.22 | 0.148 | 41.6 | 15.3 |
| 2 | 12:00 | 523 | 13.18 | 1.16 | 26.3 | 19.4 | 1.5 | 3.06 | .141 | 40.0 | 15.0 |
| 3 | 13:00 | 520 | 13.10 | 1.16 | 26.3 | 19.6 | 1.5 | 3.06 | .141 | 39.8 | 14.8 |
| 4 | 14:00 | 474 | 11.94 | 1.15 | 24.9 | 20.8 | 1.6 | 2.52 | .116 | 34.0 | 14.0 |
| 5 | 14:45 | 406 | 10.23 | 1.16 | 26.3 | 23.0 | 1.8 | 2.24 | .103 | 31.0 | 13.2 |
| 6 | 16:00 | 346 | 8.72 | 1.16 | 26.3 | 24.6 | 1.8 | 1.85 | .085 | 26.5 | 12.0 |
| 7 | 17:00 | 301 | 7.59 | 1.15 | 24.9 | 25.5 | 1.8 | 1.66 | .076 | 21.6 | 11.2 |
| 8 | 17:45 | 256 | 6.45 | 1.14 | 23.4 | 26.4 | 1.8 | 1.41 | .065 | 17.1 | 10.4 |
| 9 | 18:30 | 214 | 5.39 | 1.12 | 20.5 | 27.1 | 1.8 | 1.31 | .060 | 12.3 | 9.6 |
| 10 | 19:45 | 551 | 13.89 | 1.15 | 24.9 | 18.4 | 1.5 | 3.20 | .146 | 39.5 | 15.2 |
| SLURRY TEST 2--30 wt-pct (NOMINAL) SOLIDS | | | | | | | | | | | |
| 1 | 11:30 | 514 | 12.95 | 1.20 | 31.8 | 18.6 | 0.9 | 3.53 | 0.161 | 49.1 | 15.5 |
| 2 | 13:45 | 514 | 12.95 | 1.19 | 30.5 | 18.7 | .9 | 3.46 | .158 | 46.7 | 15.6 |
| 3 | 14:45 | 514 | 12.95 | 1.19 | 30.5 | 18.8 | 1.0 | 3.42 | .157 | 46.7 | 15.4 |
| 4 | 16:00 | 499 | 12.57 | 1.19 | 30.5 | 19.2 | 1.0 | 3.26 | .149 | 45.3 | 14.9 |
| 5 | 17:00 | 452 | 11.39 | 1.19 | 30.5 | 20.6 | 1.2 | 2.88 | .132 | 41.0 | 14.0 |
| 6 | 18:00 | 400 | 10.08 | 1.18 | 29.1 | 22.2 | 1.2 | 2.53 | .116 | 34.4 | 13.2 |
| 7 | 19:00 | 366 | 9.22 | 1.18 | 29.1 | 23.2 | 1.2 | 2.32 | .106 | 31.5 | 12.7 |
| 8 | 19:45 | 326 | 8.22 | 1.18 | 29.1 | 24.2 | 1.2 | 2.12 | .097 | 28.0 | 11.9 |
| 9 | 21:00 | 285 | 7.18 | 1.17 | 27.7 | 25.1 | 1.2 | 1.85 | .085 | 23.2 | 11.1 |
| 10 | 22:00 | 242 | 6.10 | 1.16 | 26.3 | 26.2 | 1.2 | 1.61 | .074 | 18.5 | 10.2 |
| 11 | 22:45 | 199 | 5.01 | 1.14 | 23.4 | 26.7 | 1.2 | 1.67 | .076 | 13.3 | 9.4 |
| 12 | 24:00 | 159 | 4.01 | 1.12 | 20.5 | 27.0 | 1.3 | 1.43 | .066 | 9.1 | 8.3 |
| 13 | 25:00 | 0 | .00 | 1.08 | 14.1 | NA | NA | .00 | .000 | .0 | 7.7 |
| 14 | 27:00 | 534 | 13.47 | 1.18 | 29.1 | NA | NA | 3.22 | .147 | 45.9 | 15.2 |
| SLURRY TEST 3--35 wt-pct (NOMINAL) SOLIDS | | | | | | | | | | | |
| 1 | 11:30 | 530 | 13.35 | 1.25 | 38.2 | 21.8 | 1.4 | 4.30 | 0.196 | 63.3 | 13.8 |
| 2 | 12:30 | 528 | 13.31 | 1.25 | 38.2 | 21.9 | 1.5 | 4.19 | .192 | 63.1 | 13.8 |
| 3 | 13:30 | 530 | 13.35 | 1.24 | 37.0 | 21.9 | 1.5 | 4.18 | .191 | 60.8 | 13.8 |
| 4 | 14:00 | 530 | 13.35 | 1.24 | 37.0 | 21.9 | 1.4 | 4.17 | .190 | 60.8 | 13.8 |
| 5 | 15:00 | 515 | 12.98 | 1.24 | 37.0 | 22.4 | 1.5 | 3.98 | .182 | 59.1 | 13.3 |
| 6 | 16:00 | 490 | 12.34 | 1.24 | 37.0 | 23.0 | 1.6 | 3.74 | .171 | 56.2 | 13.0 |
| 7 | 16:30 | 451 | 11.37 | 1.24 | 37.0 | 24.2 | 1.7 | 3.46 | .158 | 51.7 | 12.5 |
| 8 | 18:00 | 387 | 9.76 | 1.24 | 37.0 | 25.7 | 1.8 | 3.06 | .140 | 44.4 | 11.8 |
| 9 | 19:00 | 342 | 8.63 | 1.23 | 35.7 | 26.6 | 1.8 | 2.82 | .129 | 37.6 | 10.9 |
| 10 | 20:00 | 298 | 7.50 | 1.22 | 34.4 | 27.2 | 1.7 | 2.59 | .119 | 31.3 | 10.2 |
| 11 | 21:00 | 253 | 6.37 | 1.21 | 33.1 | 27.8 | 1.7 | 2.45 | .112 | 25.4 | 9.3 |
| 12 | 22:30 | 558 | 14.07 | 1.23 | 35.7 | 21.4 | 1.4 | 4.13 | .189 | 61.3 | 13.6 |
| SLURRY TEST 4--40 wt-pct (NOMINAL) SOLIDS | | | | | | | | | | | |
| 1 | 10:00 | 477 | 12.02 | 1.27 | 40.6 | 20.1 | 1.3 | 3.95 | 0.181 | 61.5 | 16.8 |
| 2 | 11:30 | 477 | 12.02 | 1.27 | 40.6 | 20.1 | 1.3 | 3.87 | .177 | 61.5 | 16.7 |
| 3 | 13:00 | 484 | 12.20 | 1.26 | 39.4 | 20.1 | 1.4 | 3.83 | .175 | 60.1 | 16.5 |
| 4 | 14:30 | 476 | 12.00 | 1.26 | 39.4 | 20.2 | 1.6 | 3.78 | .173 | 59.1 | 16.2 |
| 5 | 15:30 | 454 | 11.44 | 1.25 | 38.2 | 21.0 | 1.7 | 3.56 | .163 | 54.2 | 15.5 |
| 6 | 17:00 | 429 | 10.81 | 1.25 | 38.2 | 21.9 | 1.8 | 3.40 | .155 | 51.2 | 15.0 |
| 7 | 17:45 | 383 | 9.65 | 1.25 | 38.2 | 23.2 | 1.9 | 3.06 | .140 | 45.8 | 14.2 |
| 8 | 19:00 | 324 | 8.16 | 1.25 | 38.2 | NA | 1.8 | 2.76 | .126 | 38.7 | 13.0 |
| 9 | 20:15 | 266 | 6.70 | 1.23 | 35.7 | NA | 1.8 | 2.48 | .113 | 29.2 | 11.9 |
| 10 | 21:00 | 224 | 5.64 | 1.22 | 34.4 | NA | 1.8 | 2.43 | .111 | 23.5 | 10.7 |
| 11 | 22:00 | 0 | .00 | NA | NA | NA | NA | .00 | .000 | .0 | 8.1 |

See explanatory notes at end of table.

TABLE B-1. - Slurry test data--Continued

| Reading | Time,[1] min:sec | Flow, gpm | Velocity, fps | Sp gr | Solids, wt-pct | $P_d$, psi | $P_s$, psi | $P_{diff}$,[2] psi | Head loss[3] | Waste, dry tph | Power, kw |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SLURRY TEST 5--45 wt-pct (NOMINAL) SOLIDS | | | | | | | | | | | |
| 1 | 15:00 | 518 | 13.05 | 1.31 | 45.2 | 22.6 | 1.2 | 4.60 | 0.210 | 76.7 | 15.3 |
| 2 | 16:15 | 506 | 12.75 | 1.31 | 45.2 | 22.9 | 1.2 | 4.50 | .206 | 75.0 | 15.1 |
| 3 | 17:00 | 509 | 12.83 | 1.31 | 45.2 | 23.0 | 1.2 | 4.42 | .202 | 75.4 | 15.1 |
| 4 | 17:45 | 512 | 12.90 | 1.31 | 45.2 | 22.9 | 1.2 | 4.38 | .200 | 75.8 | 15.0 |
| 5 | 18:45 | 507 | 12.78 | 1.31 | 45.2 | 22.9 | 1.2 | 4.35 | .199 | 75.1 | 14.9 |
| 6 | 19:30 | 490 | 12.35 | 1.30 | 44.1 | 23.2 | 1.2 | 4.21 | .193 | 70.2 | 14.8 |
| 7 | 20:15 | 464 | 11.69 | 1.30 | 44.1 | 24.0 | 1.3 | 3.93 | .180 | 66.5 | 14.6 |
| 8 | 21:00 | 416 | 10.48 | 1.30 | 44.1 | 25.1 | 1.4 | 3.68 | .168 | 59.6 | 13.5 |
| 9 | 23:00 | 381 | 9.60 | 1.31 | 45.2 | 25.9 | 1.4 | 3.43 | .157 | 56.4 | 12.8 |
| 10 | 24:00 | 346 | 8.72 | 1.30 | 44.1 | 26.6 | 1.5 | 3.16 | .144 | 49.6 | 12.2 |
| 11 | 24:45 | 307 | 7.74 | 1.30 | 44.1 | 27.2 | 1.4 | 3.06 | .140 | 44.0 | 11.4 |
| 12 | 25:30 | 262 | 6.60 | 1.28 | 41.8 | 27.8 | 1.3 | 3.01 | .138 | 35.1 | 10.6 |
| 13 | 27:00 | 547 | 13.78 | 1.30 | 44.1 | 22.4 | 1.1 | 4.34 | .199 | 78.4 | 15.2 |
| SLURRY TEST 6--50 wt-pct (NOMINAL) SOLIDS | | | | | | | | | | | |
| 1 | 14:30 | 490 | 12.34 | 1.35 | 49.5 | 23.4 | 1.8 | 4.89 | 0.224 | 82.0 | 14.8 |
| 2 | 15:45 | 493 | 12.42 | 1.35 | 49.5 | 23.6 | 1.8 | 4.79 | .219 | 82.5 | 14.5 |
| 3 | 16:45 | 496 | 12.50 | 1.35 | 49.5 | 23.6 | 1.8 | 4.78 | .218 | 83.0 | 14.5 |
| 4 | 18:00 | 486 | 12.26 | 1.34 | 48.4 | 23.8 | 1.8 | 4.67 | .213 | 79.0 | 14.3 |
| 5 | 19:15 | 462 | 11.65 | 1.34 | 48.4 | 24.5 | 1.9 | 4.41 | .201 | 75.1 | 13.8 |
| 6 | 20:15 | 430 | 10.83 | 1.34 | 48.4 | 25.5 | 2.0 | 4.18 | .191 | 69.9 | 13.4 |
| 7 | 22:00 | 379 | 9.56 | 1.34 | 48.4 | 26.8 | 2.1 | 3.89 | .178 | 61.6 | 12.6 |
| 8 | 23:00 | 337 | 8.48 | 1.34 | 48.4 | 27.8 | 2.1 | 3.72 | .170 | 54.8 | 11.9 |
| 9 | 24:45 | 304 | 7.66 | 1.33 | 47.4 | 28.3 | 2.0 | 3.57 | .163 | 47.9 | 11.4 |
| 10 | 25:30 | 451 | 11.37 | 1.33 | 47.4 | 25.2 | 2.0 | 4.07 | .186 | 71.1 | 13.3 |
| 11 | 26:30 | 527 | 13.29 | 1.33 | 47.4 | 23.1 | 1.8 | 4.68 | .214 | 83.1 | 14.2 |
| SLURRY TEST 7--55 wt-pct (NOMINAL) SOLIDS | | | | | | | | | | | |
| 1 | 15:30 | 465 | 11.71 | 1.41 | 55.5 | 24.6 | 1.8 | 5.65 | 0.258 | 91.1 | 17.3 |
| 2 | 17:00 | 465 | 11.71 | 1.40 | 54.5 | 24.9 | 2.1 | 5.55 | .254 | 88.9 | 17.2 |
| 3 | 18:00 | 466 | 11.75 | 1.40 | 54.5 | 24.8 | 2.1 | 5.51 | .252 | 89.1 | 17.0 |
| 4 | 19:15 | 461 | 11.61 | 1.40 | 54.5 | 25.1 | 2.2 | 5.32 | .243 | 88.1 | 16.9 |
| 5 | 20:30 | 441 | 11.10 | 1.39 | 53.6 | 25.8 | 2.2 | 5.13 | .235 | 82.2 | 16.4 |
| 6 | 22:00 | 414 | 10.44 | 1.39 | 53.6 | 26.3 | 2.2 | 4.82 | .221 | 77.2 | 15.8 |
| 7 | 23:45 | 375 | 9.44 | 1.39 | 53.6 | 27.4 | 2.2 | 4.59 | .210 | 69.9 | 15.2 |
| 8 | 24:45 | 333 | 8.40 | 1.39 | 53.6 | 28.2 | 2.1 | 4.43 | .203 | 62.1 | 14.3 |
| 9 | 26:00 | 292 | 7.35 | 1.38 | 52.6 | 28.7 | 2.1 | 4.18 | .191 | 53.0 | 13.0 |
| 10 | 28:00 | 518 | 13.06 | 1.38 | 52.6 | 24.5 | 1.8 | 5.23 | .239 | 94.1 | 17.2 |
| SLURRY TEST 8--60 wt-pct (NOMINAL) SOLIDS | | | | | | | | | | | |
| 1 | 13:00 | 477 | 12.02 | 1.46 | 60.1 | 25.2 | 1.4 | 5.57 | 0.255 | 104.8 | 17.4 |
| 2 | 14:45 | 477 | 12.02 | 1.46 | 60.1 | 25.4 | 1.8 | 5.46 | .250 | 104.8 | 17.3 |
| 3 | 15:45 | 483 | 12.16 | 1.46 | 60.1 | 25.3 | 1.9 | 5.36 | .245 | 106.2 | 17.3 |
| 4 | 16:45 | 480 | 12.10 | 1.46 | 60.1 | 25.5 | 2.0 | 5.30 | .243 | 105.5 | 17.1 |
| 5 | 18:00 | 452 | 11.38 | 1.46 | 60.1 | 26.2 | 2.4 | 5.00 | .229 | 99.4 | 16.4 |
| 6 | 19:00 | 410 | 10.32 | 1.46 | 60.1 | 27.4 | 2.5 | 4.80 | .219 | 90.1 | 15.8 |
| 7 | 20:00 | 369 | 9.29 | 1.46 | 60.1 | 28.4 | 2.7 | 4.54 | .207 | 81.1 | 15.0 |
| 8 | 21:15 | 324 | 8.15 | 1.46 | 60.1 | 29.4 | 2.7 | 4.40 | .201 | 71.2 | 14.0 |
| 9 | 22:15 | 283 | 7.14 | 1.45 | 59.2 | 30.0 | 2.6 | 4.30 | .196 | 60.9 | 13.2 |
| 10 | 23:30 | 228 | 5.74 | 1.44 | 58.3 | 30.5 | 2.4 | 4.40 | .201 | 47.9 | 11.9 |
| 11 | 25:00 | 511 | 12.89 | 1.44 | 58.3 | 25.1 | 1.9 | 5.09 | .233 | 107.4 | 16.9 |

NA Not available.

[1]Elapsed from beginning of test.

[2]Across 50.48-ft straight pipe section.

[3]Feet of water per foot of pipe.

TABLE B-2. – Clear water test data

| Reading | Time,[1] min:sec | Flow, gpm | Velocity, fps | $P_d$, psi | $P_s$, psi | $P_{diff}$,[2] psi | Head loss[3] | Power, kw |
|---|---|---|---|---|---|---|---|---|
| 1 | 1:00 | 626 | 15.78 | 18.0 | 0.6 | 3.42 | 0.156 | 11.2 |
| 2 | 1:45 | 618 | 15.57 | 18.4 | .7 | 3.31 | .151 | 11.1 |
| 3 | 2:45 | 618 | 15.57 | 18.2 | .6 | 3.31 | .152 | 11.0 |
| 4 | 3:30 | 615 | 15.50 | 18.2 | .6 | 3.31 | .151 | 11.0 |
| 5 | 4:15 | 598 | 15.07 | 18.7 | .8 | 3.15 | .144 | 11.0 |
| 6 | 5:15 | 573 | 14.44 | 19.3 | .8 | 2.92 | .133 | 10.7 |
| 7 | 6:15 | 531 | 13.38 | 20.2 | .9 | 2.50 | .114 | 10.3 |
| 8 | 7:00 | 482 | 12.15 | 21.2 | 1.1 | 2.07 | .095 | 10.0 |
| 9 | 8:00 | 428 | 10.79 | 22.3 | 1.2 | 1.67 | .076 | 9.4 |
| 10 | 9:15 | 378 | 9.53 | 23.2 | 1.3 | 1.31 | .060 | 9.0 |
| 11 | 10:15 | 330 | 8.32 | 23.8 | 1.4 | 1.01 | .046 | 8.5 |
| 12 | 11:00 | 270 | 6.80 | 24.9 | 1.4 | .71 | .033 | 7.9 |
| 13 | 11:45 | 197 | 4.96 | 25.7 | 1.5 | .46 | .021 | 7.4 |
| 14 | 12:30 | 160 | 4.03 | 26.2 | 1.6 | .28 | .013 | 6.8 |
| 15 | 13:30 | 108 | 2.72 | 26.5 | 1.6 | .13 | .006 | 6.4 |
| 16 | 14:30 | 64 | 1.61 | 26.6 | 1.6 | .05 | .002 | 6.0 |
| 17 | 15:15 | 30 | .76 | 26.6 | 1.7 | .00 | .000 | 5.8 |
| 18 | 16:00 | 11 | .28 | 26.8 | 1.8 | .00 | .000 | 5.7 |
| 19 | 17:15 | 2 | .05 | 26.8 | 1.8 | .00 | .000 | 5.6 |
| 20 | 18:30 | 625 | 15.75 | 18.0 | .6 | 3.38 | .155 | 11.0 |

[1]Elapsed from beginning of test.
[2]Across 50.48-ft straight pipe section.
[3]Feet of water per foot of pipe.

## APPENDIX C.--FRICTION-PRESSURE GRADIENT POLYNOMIAL FUNCTIONS

In the following table are the polynomial equations for use in determining the friction-pressure gradient ($H_f$, in feet of water per foot of pipe) from velocity (V, in feet per second). A different equation exists for each weight-percent coal waste solids level and for clear water. It must be kept in mind that these equations are valid for projecting friction loss *only* in 4-in standard steel pipe.

TABLE C-1. - Friction-loss polynomial equations

| Nominal coal-waste solids, wt-pct | Polynomial equation | Index[1] |
|---|---|---|
| 25..... | $H_f = 5.00 \times 10^{-2} - 1.60 \times 10^{-3} (V) + 6.38 \times 10^{-4} (V^2)$ | 0.994 |
| 30..... | $H_f = 7.48 \times 10^{-3} + 1.14 \times 10^{-2} (V) - 1.58 \times 10^{-6} (V^2)$ | .979 |
| 35..... | $H_f = 1.28 \times 10^{-1} - 8.82 \times 10^{-3} (V) + 1.02 \times 10^{-3} (V^2)$ | .995 |
| 40..... | $H_f = 2.80 \times 10^{-3} + 1.92 \times 10^{-2} (V) - 4.26 \times 10^{-4} (V^2)$ | .984 |
| 45..... | $H_f = 1.84 \times 10^{-1} - 1.61 \times 10^{-2} (V) + 1.36 \times 10^{-3} (V^2)$ | .988 |
| 50..... | $H_f = 2.24 \times 10^{-1} - 1.93 \times 10^{-2} (V) + 1.51 \times 10^{-3} (V^2)$ | .995 |
| 55..... | $H_f = 3.21 \times 10^{-1} - 3.66 \times 10^{-2} (V) + 2.62 \times 10^{-3} (V^2)$ | .972 |
| 60..... | $H_f = 2.98 \times 10^{-1} - 2.85 \times 10^{-2} (V) + 2.01 \times 10^{-3} (V^2)$ | .964 |
| Clear water..... | $H_f = 5.04 \times 10^{-4} + 1.07 \times 10^{-3} (V) + 5.61 \times 10^{-4} (V^2)$ | 1.000 |

[1]The index of determination, defined as

$$I = 1 - \frac{\Sigma (y_i - \tilde{y}_i)^2}{\Sigma (y_i - \bar{y})^2}.$$

If the model being tested is linear, the index of determination is equivalent to either the correlation coefficient or the multiple correlation coefficient. This index is useful in that it can be used to compare goodness-of-fit of nonlinear models. The index ranges from 0 to 1, with 1 being a perfect fit.

☆U.S. GOVERNMENT PRINTING OFFICE: 1983-705-020/88

INT.-BU.OF MINES,PGH.,PA. 27185