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EXPERIMENTAL VERIFICATION OF A PNEUMATIC TRANSPORT SYSTEM FOR THE RAPID EXCAVATION OF TUNNELS
PART II - TEST PROGRAM

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FINAL REPORT

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16. Abstract

The objective of the study was to evaluate a pneumatic pipeline system for muck haulage from a tunnel excavated by a tunnel boring machine. The system was comprised of a muck preparation unit, solids feeder and air blower, telescoping pipes and 500 feet of 10-inch diameter pipe. The system transported up to 100 tph of simulated tunnel muck with maximum sizes ranging from 1/2 inch to more than 3 inches. The system components were tested for reliability and flexibility, wear and maintenance requirements, capacity, noise and dust levels, effect of moisture content, extensibility, and power requirements.

The system was found to be low in capital cost, easy to operate, and readily extensible. The pneumatic pipeline was power-intensive and susceptible to elbow wear. For the pneumatic transport of coarse muck, moisture content was more important than particle size. Noise levels were high at the blower and muck preparation unit but could be reduced in actual practice. The system was found to be reliable except for the elbow wear.

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PREFACE

This final report presents the results of an evaluative study of a pneumatic pipeline system for muck haulage from a tunnel excavated by a tunnel boring machine. The system components were tested for reliability, flexibility, wear and maintenance requirements, capacity, noise and dust levels, effects of moisture content, extensibility, and power requirements. This study, sponsored by the U.S. Department of Transportation, Office of Rail and Construction Technology, Office of Technology Development and Deployment of the Urban Mass Transportation Administration is under contract to the Research and Special Programs Administration's Transportation Systems Center, Contract DOT-TSC-1144, for the Urban Rail Construction Technology program.

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Because of the magnitude and duration of the project, many people were involved. The authors wish to thank in particular the following students: William Skelly, Dan Shearer, Steve Rasey, Frank Tagge, David Rak, Doug Dutton, Paul Martin, and Ken Kosta.

Special thanks are extended to Mr. Doug Case of Specification Aggregates, Inc. (Holloway Construction) who graciously donated an excellent site for the test installation for almost a two-year period. The quarry company's total cooperation and generous assistance were instrumental in the successful operation of the test program.

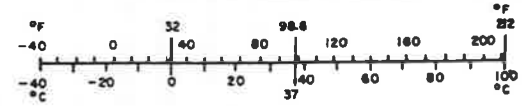
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. INTRODUCTION

As the excavation rate of tunnel boring machines has increased, the transport of muck from the machine to the disposal area has become a controlling consideration. Efforts to increase muck handling capabilities have directed attention towards continuous haulage systems such as pipelines.

This study is the final phase of a muck pipeline program begun in 1973. The following reports have been issued:

Ref. 1. Faddick, R.R., and J.W. Martin, "Pneumatic-Hydraulic Material Transport System for Rapid Excavation of Tunnels," DOT-TST-75-17, August, 1974.

Ref. 2. Martin, J.W., and R.R. Faddick, "Experimental Verification of a Pneumatic Transport System for the Rapid Excavation of Tunnels, Part I. Installation of Test Facility," DOT-TST-76-63, March, 1976.

Ref. 3. Faddick, R.R., and J.W. Martin, "The Transportation of Tunnel Muck by Pipeline," UMTA-MA-06-0025-78-4, January, 1978.

In addition, a 16mm color movie with sound track has been made of the test program. Copies are available on loan from the U.S. Department of Transportation, Transportation Systems Center, Cambridge MA, and from the authors, c/o the Basic Engineering Department, Colorado School of Mines, Golden CO 80401.

The third report is essentially a companion or supplemental report to the first and second reports. The thrust of all these studies was to investigate the potential use of a muck haulage pipeline, either pneumatic or slurry. As the studies progressed, it became evident that considerable knowledge and experience had been accumulated on the application of slurry pipelines to a wide variety of materials for transport. Comparable information on pneumatic transport systems was much more limited, particularly with respect to the handling of coarse, abrasive materials such as tunnel muck. Consequently, field tests were performed solely on a pneumatic pipeline system, the installation of which is described in Ref. 2.

There are three possible applications of a pneumatic system to tunneling. The first is a complete main haulage unit limited to maximum lengths on the order of 1000 to 2000 ft. The second is a short intermediate link between a slurry pipeline and the tunneling machine to provide a means for continuous operational extension to match the advance of the tunnel excavation. In both cases it is assumed that continuous muck haulage is achieved by the pneumatic system with telescopic pipe sections providing sufficient extensibility. During periodic shutdowns, scheduled to include repair and maintenance activities, the telescoped pipe would be retracted and pipe added to the line in proportion to the advance achieved in the prior operational period. The third application involves hoisting muck up a deep shaft, such as excavation of a deep subway station. The essence of the three applications was duplicated at the test site by running the pneumatic pipeline up a steep hill to simulate hoisting, laying the pipeline flat to simulate horizontal haulage, and operating the pipeline with telescoping pipe in series. Equipment wear associated with some of these transport configurations was also studied.

2. TEST PROGRAMS

The objectives of the study were to test the pneumatic transport facility for the following:

1. Muck Preparation Unit
   a) reliability
   b) wear and maintenance requirements
   c) capacity
   d) noise levels
   e) energy requirements and operating costs
2. Pneumatic Conveyance System
   a) reliability and flexibility
   b) wear and maintenance requirements
   c) capacity
   d) noise and dust levels
   e) energy requirements and operating costs
   f) effect of moisture content
   g) extensibility.
3. Particle size and distribution are usually considered the keys to efficient pipeline transportation. A different particle size distribution may exist for optimum slurry and pneumatic conveyance. The optimum size distribution for pipeline transportation must be compatible with muck preparation costs and give acceptable operational performance. Data from Nos. 1 and 2 above were to be obtained for several particle size distributions.

While the outlined test program was meant to be comprehensive, it was recognized that it would be modified based upon weather, muck characteristics, or operational inadequacies.

In order to simulate potential applications of a pneumatic pipeline (horizontal transport, vertical transport, and extensibility) while studying the previously mentioned characteristics, two pipeline configurations were installed:

first, a steeply inclined pipeline to simulate muck hoisting, and second, a horizontal pipeline to expedite wear testing. Extensibility was studied in the horizontal loop toward the end of the test program. The performance characteristics listed above were reduced to four general test programs:

High Lift-High Capacity Tests (inclined pipeline)
Wear Tests (horizontal pipeline)
Extensibility Tests (horizontal pipeline)
Noise Level Tests (inclined pipeline)

The development of each program is described here in detail, and the results of each are discussed in the ensuing sections.

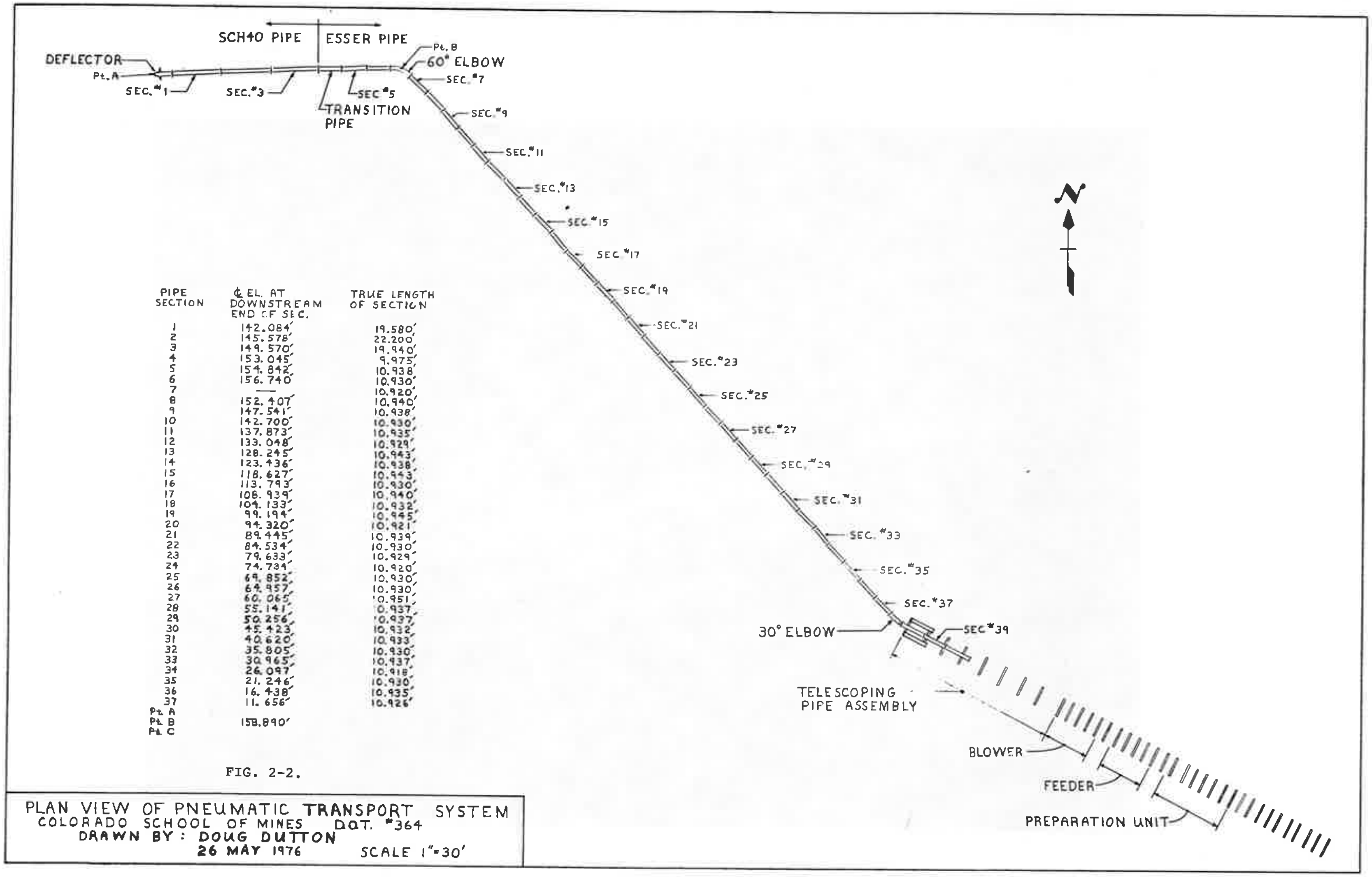
2.1 HIGH LIFT-HIGH CAPACITY TESTS - INCLINED PIPELINE

Part I (Ref. 2) contains photos of the inclined pipeline configuration and an extensive description of the pneumatic pipeline system comprising a muck preparation unit, blower, feeder, and telescoping pipes. Fig. 2-1 (photo) views the pipeline from its uppermost point. Fig. 2-2 is a plan view drawing of the pipeline with various elevations indicated. The incline was approximately 26° or 48% with a slope length of about 352 ft. The vertical lift was about 160 ft. from the pipe C_L at the feeder to the tangent intersection of the 60° flatback bend. The pipeline then continued about 150 ft. slightly downward, terminating at a deflector discharging into a gully.

A completely vertical lift would have been prohibitively expensive in view of the pipe supports required. Thus, this inclined configuration was regarded as a compromise for simulating vertical lift. From a pneumatic pipeline viewpoint, an inclined pipe is worse than a vertical pipeline because wear is more severe and power requirements increase with pipe inclination (3).

A water ring was in the pipeline near the deflector but was not used because of the expense in pumping water

FIG. 2-1. General Layout of Capacity Test Pipeline Configuration



PIPE SECTION	℄ EL. AT DOWNSTREAM END OF SEC.	TRUE LENGTH OF SECTION
1	142.084'	19.580'
2	145.578'	22.200'
3	149.570'	19.940'
4	153.045'	9.975'
5	154.842'	10.938'
6	156.740'	10.930'
7	—	10.920'
8	152.407'	10.940'
9	147.541'	10.938'
10	142.700'	10.930'
11	137.873'	10.935'
12	133.048'	10.929'
13	128.245'	10.943'
14	123.436'	10.938'
15	118.627'	10.943'
16	113.793'	10.930'
17	108.939'	10.940'
18	104.133'	10.932'
19	99.194'	10.945'
20	94.320'	10.921'
21	89.445'	10.939'
22	84.534'	10.930'
23	79.633'	10.929'
24	74.734'	10.920'
25	69.852'	10.930'
26	64.957'	10.930'
27	60.065'	10.951'
28	55.141'	10.937'
29	50.256'	10.937'
30	45.423'	10.932'
31	40.620'	10.933'
32	35.805'	10.930'
33	30.965'	10.937'
34	26.097'	10.918'
35	21.246'	10.930'
36	16.438'	10.935'
37	11.656'	10.926'
Pt. A		
Pt. B	158.890'	
Pt. C		

FIG. 2-2.

FIG. 2-2. Plan View of Pneumatic Transport System up 150 ft. In any case, dust control was not required during the tests for the coarse solids transported. The only objectionable dust observed was the initial cleanout of the pipeline after installation. This disappeared after a few minutes.

The purpose of the tests was to demonstrate that simulated coarse tunnel muck could be readily lifted 150 ft. in large tonnages. Because the aggregate blown through the pipeline could not be reclaimed from the top of the hill, the duration of these tests was purposely kept short to reduce the cost of aggregate. Essentially five different muck sizes and a ranges of tonnage rates up to 100 ton/hr were conveyed in a total of ten tests. Moisture content was varied by simply watering the various piles of aggregate prior to feeding the pneumatic pipeline system. Each test was of at least 15 minutes duration because the electrical power meters recorded demand levels every quarter hour.

Crushing was performed during each of the ten tests, but power requirements varied according to the size distribution and vibratory screen size.

The test procedure was a follows:

1. Aggregate piles were prepared for feeding and wetted as required.
2. The pipeline system was checked according to prescribed maintenance schedules.
3. The system was operated with air only for several minutes to bring airflow up to temperature and to check for pipe leaks. Air velocity profiles were measured at pipe section #1 (Fig. 2-2) as required.
4. Front-end loader commenced dumping at the start of a designated 15-minute time interval. Dumping was regulated by the loader-operator such that the surge hopper above the Radmark feeder was never overloaded. A convex mirror above the surge hopper enabled the loader-operator to pace himself.
5. When the loader bucket was emptied, the operator trammed back to the aggregate pile for a refill.

Cycle time was less than a minute and did not leave the surge hopper empty. Thus, continuous filling of the Radmark feeder was assured. See Fig. 2-3(photo).

6. During the 15-minute cycle, the console operator recorded system pressures, air temperature, and Syntron pan feeder settings. A second person recorded the power consumption by all units and a third person collected bucket samples of aggregates falling from the inclined conveyor belt into the surge hopper. These samples were analyzed for size distribution and moisture content. The third person also walked the pipeline checking for wear leaks and checked the power units for possible maintenance problems.
7. At the end of a continuous 15-minute run the system was either shut down or continued to operate for another test involving either the same muck with a different moisture content or another muck size distribution.
8. Occasionally, a 15-minute run was interrupted by muck unit conveyor belt misalignments, V-belt turnovers on the drives of the muck unit conveyors, or "gunking up" of the Syntron feeder pan and Radmark feeder trough due to excessively moist fines. Once the problem was corrected, a new 15-minute run was begun.

The complete test description and results are given in Section 5.

Wear was not studied with this pipeline configuration. It was recognized that the 30° and 60° flatback bends, because of their orientation, were not receiving localized impingements, but distributed the solids uniformly over the wearing surface of the bend.

Extensibility of the telescoping sections was not attempted during these tests. (See Section 7.)

Noise level measurements were taken during these tests and are reported in Section 8.

FIG. 2-3. Loading System with Muck

2.2 WEAR TESTS - HORIZONTAL PIPELINE

Upon completion of the high lift-high capacity tests, the pipeline was removed from the hill and connected on a horizontal plane in a rectangular pattern discharging through the deflector into a slot cut into the side of a hill. This enabled easy retrieval of the transported aggregate. See Fig. 2-4 (photo) and Fig. 2-5.

The purpose of these tests was to attempt to determine wear life of the various system components. These included the impact bars in the crusher, Radmark feeder jaws, telescoping pipe, Esser (hardened steel) pipe, assorted elbows, and the deflector. It was assumed that the elbows would suffer the severest wear so attention was given to accelerating their wear even more. The rectangular pipeline configuration satisfied several requirements:

a) Four bends were required, allowing a varied assortment of bends to be tested.

FIG. 2-4. General Layout of Wear Test Pipeline Configuration

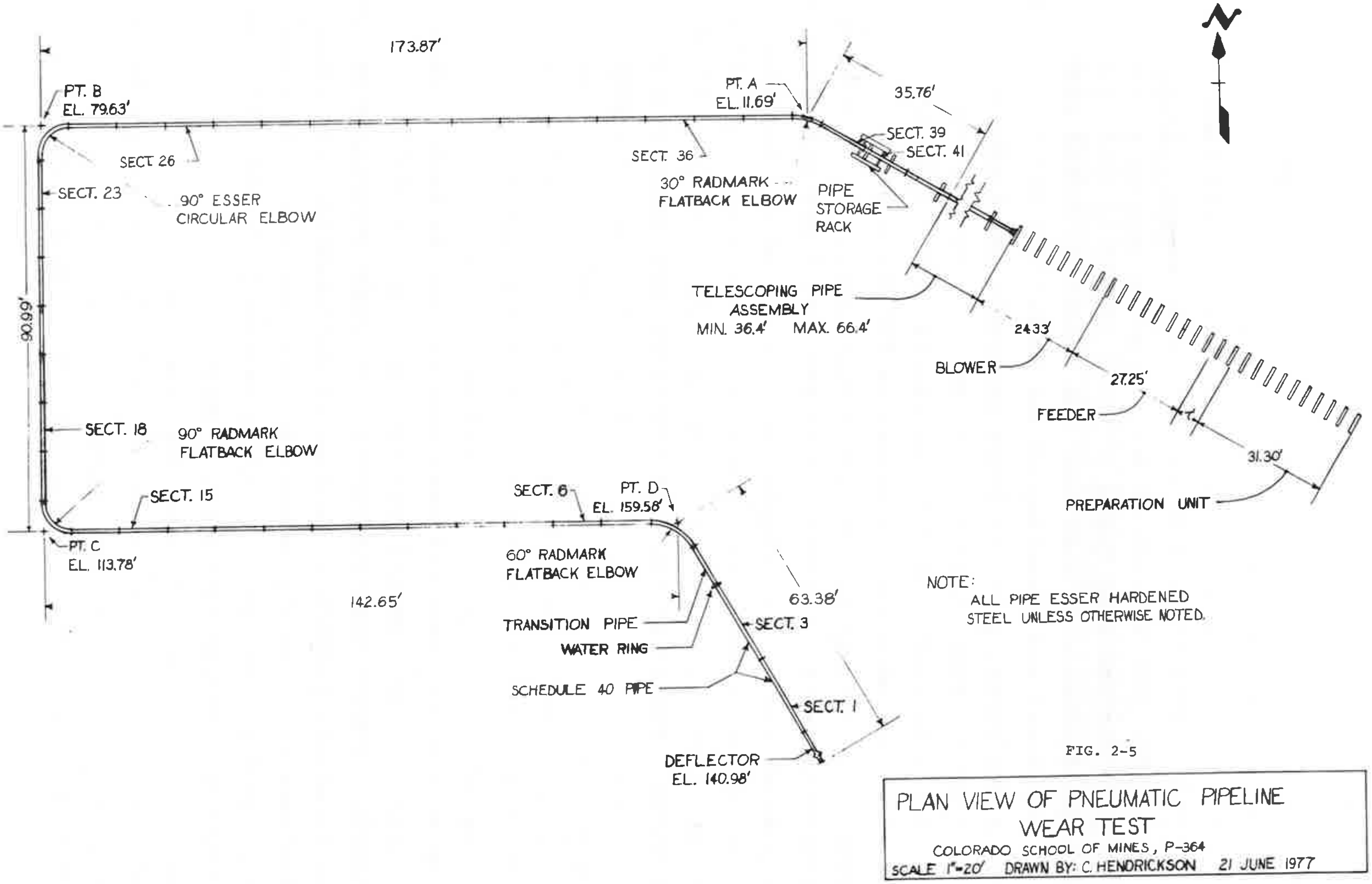


FIG. 2-5. Plan View of Pneumatic Pipeline Wear Test

b) Such a large number of bends increases pressure drop substantially, allowing the system to operate at essentially full blower capacity, yet allowing only medium tonnage rates to be transported. This reduces the handling of very large volumes of aggregate for the wear tests.

c) The discharge of muck near the feeder permitted easy retrieval and recycling of the muck.

d) A horizontal plane is least desirable for flatback elbows. Wear is accelerated by localized impingements of solids on the wear liners of the elbows.

e) Flat unused space was available for the pipeline.

Some modifications of the system were necessary. The train of equipment (muck unit, feeder and blower skids) was pulled southeasterly along its ties to enable rotation of the 30° flatback elbow into a horizontal plane such that the rectangular pipeline fit the available space without undue excavation of the hillside on the north. The water ring was installed just downstream of the 60° elbow so that it was within reach of the water supply pumping system. Recycling of the muck was expected to generate more fines and hence more dust, thus requiring a need for water. The deflector at the end of the pipeline was adjusted upward to give a higher trajectory into the hillside slot.

Due to the complexity of wear testing and its lack of documented data, a predetermined wear test program was highly speculative. Budget and time constraints would eventually prevail, but the immediate problem was equipment reliability. Any equipment failures could easily curtail the test program. Therefore, it was decided to test on virtually a day-to-day basis with only a very general program outline as a guide.

Two sets of wear tests were performed, one in 1976 and one in 1977 with a dead period in the winter. The variables studied, in addition to different elbow types, were elbow liners and muck size distributions. The wear tests are discussed in detail in Section 6.

3. MUCK IDENTIFICATION

The test installation was located at the Specification Aggregates, Inc. quarry one mile south of the Golden city limits on U.S. Hwy. 40. The company produces crushed stone for concrete aggregate, road base mixtures and custom sized fills for major earth-rock dam construction projects in the Denver area. Hard crushed rock with assorted gradation characteristics was readily available on the site for the test program.

Rock quarried at the Specification Aggregates site is composed of metamorphic quartzo-feldspathic gneisses and dark-gray hornblende-biotite gneisses, containing numerous intrusive segregations of granite pegmatite (4). Due to the extreme variations in jointing, weathering, mineralogy and structure observed from one layer to another, detailed studies of petrography and mechanical rock properties were not undertaken.

A survey was made across the upper quarry bench, using a Schmidt concrete test hammer. The survey indicated that most layers of rock would be classified as "hard" (see Ref. 5). For hardest concretes, a reading of about 55 is obtained with the Schmidt hammer. From the gneisses and pegmatites, average readings of 50 to 48 were obtained, respectively.

The following properties have been reported (5,6) for rock types similar to those found at the Specification Aggregate Quarry:

	Gneisses	Pegmatites
Specific Gravity	2.65	2.60
Bulk wt. (pcf)	166	163
Hardness	5 to 7	6 to 7
Unconfined Compressive Strength (psi)	9 to 28,000	15 to 33,000
Modulus of Elasticity (psi)	6 to $8x10^6$	$6x10^6$

Four types of rock were purchased from Specification Aggregate for use at the test installation:

1. crusher fines (1/2 in. maximum size)
2. 3/4 in. road base
3. 1-1/2 in. road base
4. 3 in. rock.

Products 1, 2 and 3 were used in the muck rate calibration procedure. Products 2, 3, and 4 were input to the system during capacity and wear tests. Gradation curves from samples of the latter products are provided in Fig. 3-1.

For the capacity and wear tests, separate stockpiles of 3/4 in. road base, 1-1/2 in. road base and 3 in. rock were acquired. By changing the screen size in the preparation unit and selecting different aggregate mixtures from the various stockpiles, a range of muck types was produced for input to the pipeline. Changing the screen was a means of regulating the amount of oversize material scalped and diverted to the crusher under a given set of operating conditions. The following pipeline muck types were utilized in the capacity test series:

PIPELINE MUCK	STOCKPILE	SCREEN SIZE	TESTS*
A.	3/4 in. road base	1/2 in.	I-1,2
B.	3/4 in. road base	1 in.	I-3
C.	1-1/2 in. road base	1 in.	I-4,5
D.	1-1/2 in. road base	1-1/2 in.	I-6,7
E.	1-1/2 in. road base & 3 in. rock(blended)	1-1/2 in.	I-8, 9.

The arbitrary system of letter designations indicated above was adopted for describing test pipeline muck size characteristics. A number of standard methods for classifying

*See Table 5-1 for more details.

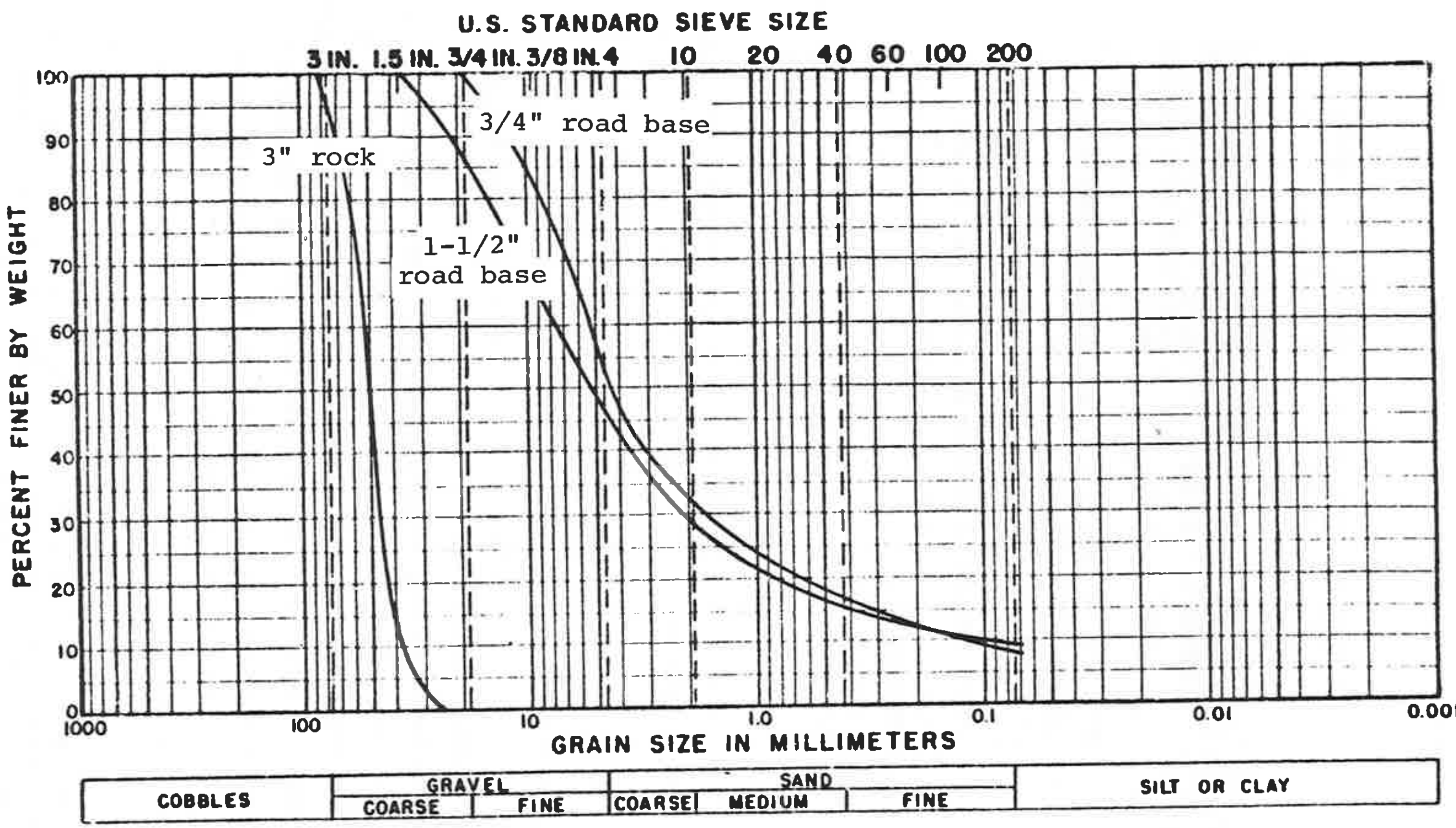


FIG. 3-1. Size Gradations of Aggregate prior to Testing

soil and crushed rock were considered for the muck description, but proved to be unsuitable for this purpose.

Muck Type	USCS[1]	HRB[2]	FAA[3]	MDN[4]
A	SW	A-1a,b	E-1,2	7
B	SW	A-1b	E-1,2	7
C	SW-GW	A-1a,b	E-2	6-7
D	SW-GW	A-1a	E-2	6
E	GW	A-1a	E-2	4-6

1. Unified Soil Classification System-U.S. Army Corps of Engineers.
2. Soil Classification Systems adopted by the Highway Research Board, American Association of State Highway Officials.
3. Federal Aviation Agency Classification System.
4. Correspondence with Muck Designation Number system considering size characteristics of muck types only.

The USCS, HRB and FAA classification systems are insensitive to changes in size characteristics of coarse aggregate mixtures. The Muck Designation Number (MDN) system of Holmes and Narver is the most workable alternative to the various schemes examined, but its application in this present context is not wholly consistent with original format as defined (Ref. 7).

Standard methods for describing aggregate and base course mixtures for highway construction have been adopted by the American Society for Testing Materials (ASTM) as Specifications D-448-54 and D-1241-68. These systems were also found to lack sufficient flexibility to be useful as methods of classification for the test pipeline muck.

In the sequence of capacity tests (described in Section 5), moisture contents* of aggregate mixtures were also varied.

*Moisture content is the ratio of the weight of included water in a sample to the total weight of sample, expressed as a percent of the total weight.

The purpose of this aspect of the test program was to study the effects of muck moisture on system performance.

Generally, it is not possible to achieve very high moisture contents in coarse aggregate mixtures if drainage is permitted. Under these conditions, maximum moisture content is limited by what is termed the "field capacity" of the mixture, which is defined as "the quantity of water held in a soil by capillary action after gravitational water is removed" (Ref. 8). For the aggregate moistures studied in the test program, field capacities ranged from about 6 to 10 percent. Generally, field capacity is increased with the proportion of minus 40 mesh (0.35mm) material in the mixture.

For the test program the following designations were assigned for moisture, arbitrarily based on weight loss determinations of samples taken from field tests:

Moisture Designations

Moisture	Designations
0-1.9%	Dry
2-3.9%	Moist
4-6.9%	Wet
+7%	Very Wet.

4. CALIBRATION AND INSTRUMENTATION

4.1 SYNTRON FEEDER CALIBRATION

The energy expended in moving muck through a pipeline and the corresponding power requirements of a pneumatic transport system may be expected to vary with the rate of muck input to the system. In order to describe specific operating characteristics of the test transport system, a method had to be devised for gauging the quantity of material delivered to the system within a prescribed interval of time.

In operation at the test installation, muck was initially put into the screening and sizing units of the transport system in surges, and flow through the muck preparation unit tended to reflect the original condition of surge feeding. Sized material, however, was delivered to a surge hopper, which offered sufficient storage to effectively isolate the pipeline feeder from surging throughput conditions. Muck from the surge hopper fell onto a Syntron vibratory feeder which provided a uniform, regulated flow of material into the top of the pipeline rotary feeder.

Measurement of muck flow rates proved to be one of the more difficult operations to perform reliably in the test program. Several methods were considered for establishing muck feed rates into the pipeline. Two methods were examined in detail:

A. Installation of a continuous weigh-load device beneath the belt which delivers material into the surge hopper

B. Direct measurement of flow rates of material from the Syntron pan for specific control settings.

Continuous weigh-load devices (weightometers) are commercially available, and are frequently installed in industrial conveyor systems to monitor throughput rates. Although such a device would appear to be readily adaptable for muck rate calibration in the test installation, several significant disadvantages were anticipated:

1. The configuration of the main conveyor belt feeding material to the surge hopper was poorly suited to weightometer installation. The belt was short and steep; weigh-load devices are best suited to installations on long, horizontal belts.
2. Measurement of muck flow rates ahead of the surge hopper would not accurately reflect flow characteristics of material entering the pipeline in the same interval of measurement.

At the same time that weigh-load devices were being considered, conversations with the manufacturers of the pneumatic system and the vibratory feeder in the test system indicated that the feeder controls could be calibrated directly to provide flow rates with a relatively high degree of accuracy (2%).

Unfortunately, the trough (pan) of the vibratory feeder in the test installation was made short to simulate actual tunnel size constraints, and the trough was not operated in a level position, due to the slope of the test site. Both conditions detracted from the unit's optimum performance. Careful observations of muck-flow characteristics in the vibratory feeder suggested that the flow was only uniform as an approximation.

Despite these limitations, this measuring method was preferred over a weigh-load installation for several reasons:

1. Because the vibratory feeder delivers material directly to the pipeline feeder in normal operations, it is the ideal point in the system for measuring throughput rates.
2. The flow may be observed directly during the measurement procedure.
3. Factors such as particle size and moisture content which exert significant influences on muck flow characteristics from the vibratory feeder could be correlated with samples obtained during the test.

The second measuring method was employed in the testing procedure.

4.2 CALIBRATION PROCEDURE

The Syntron vibratory feeder is designed to provide a uniform material feed characteristic over a range of throughput rates. A variable potentiometer with a scale range from 0 to 100 was used to adjust the rate of discharge from the unit into the pipeline feeder.

The calibration procedure utilized the following:

1. Temporary chute to divert vibratory feeder output into drum. (Fig. 4-1)
2. 55-gal. drum with lifting harness.
3. 1000-lb. capacity weigh scale.
4. Front-end loader and operator.
5. 5 persons to perform the calibration (3 to clear the chute, 1 to operate Syntron control and stopwatch, 1 to coordinate activities and man preparation unit controls.

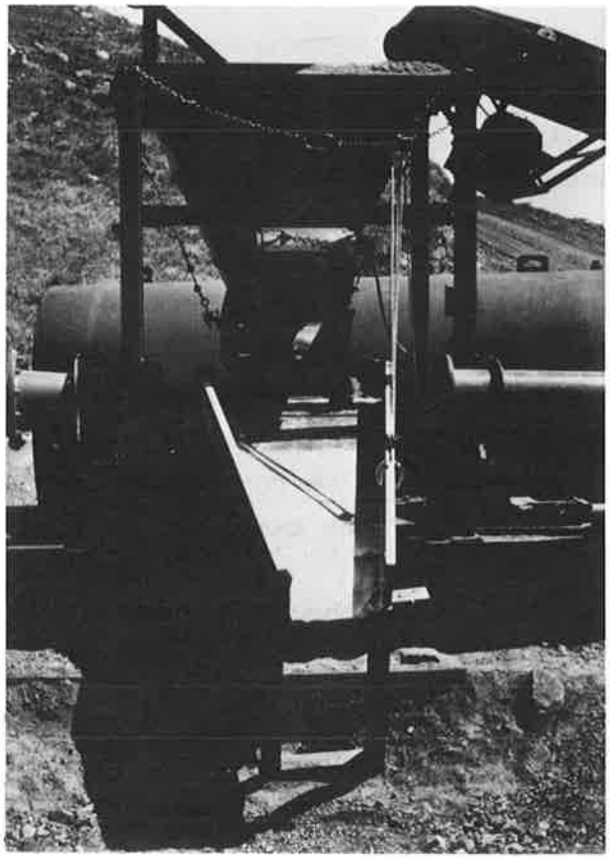


FIG. 4-1. Temporary Calibration Chute

Before proceeding with the calibration, the weigh scale was zeroed, the loader operator was advised of the test procedure, and power to the muck preparation unit was switched on. The calibration procedure was performed as follows:

1. Fill surge hopper with desired muck following a standard procedure of feeding the preparation unit with a front-end loader from rock of known size distribution and moisture content.
   (a) With Syntron at desired feed setting, operate vibratory feeder for 10-15 seconds, until the height of muck in the trough reaches steady state.

(b) Clean diverting chute of any muck.

(c) Place and empty 55-gal. drum of known weight below the diverting chute.

2. Measure Syntron Discharge

(a) The vibratory feeder was started and the material flow carefully watched for any irregularities. The test was continued until the drum was nearly full while the elapsed time was recorded with a stopwatch.

(b) Students used shovels to be sure there was no build-up in the chute which would disturb the feeder output. The test was stopped with the drum about 2/3 full. The remaining muck on the chute was shoveled into the drum with care being exercised to see that the Syntron trough remained full to its discharge lip duplicating the start conditions. Samples were taken regularly for moisture content determination. (Fig. 4-2)

3. Feed Rate Determination

(a) Loaded drum was hoisted onto the weigh scale, using the front-end loader (Fig. 4-3).

(b) Gross weight of muck plus can was recorded (Fig. 4-4).

(c) To obtain data in tons per hour:

$$STPH = \frac{(\text{lbs drum + muck}) - (\text{lbs drum})}{\text{runtime in seconds}} \times \frac{1 \text{ ton}}{2000 \text{ lbs}} \times \frac{3600 \text{ seconds}}{1 \text{ hour}}$$

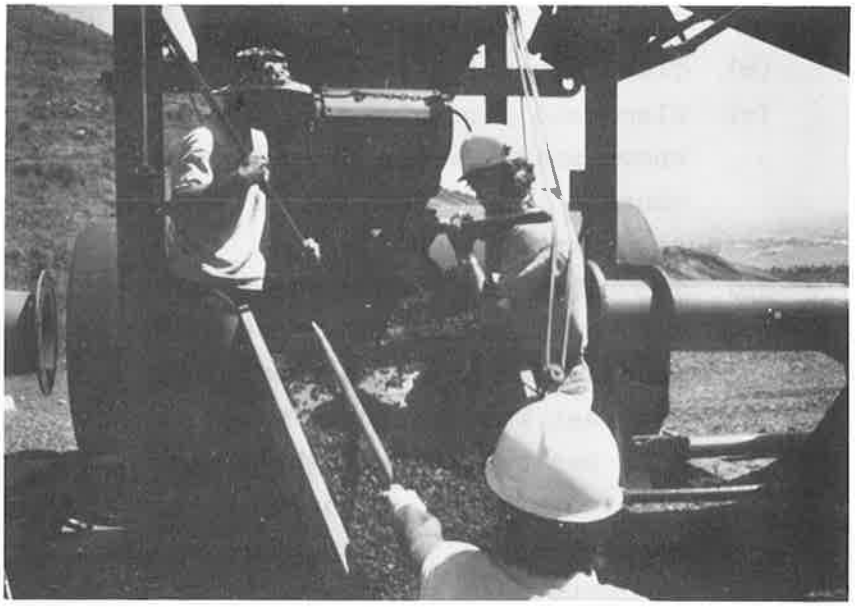


FIG. 4-2. Muck Collected for Weighing

FIG. 4-3. Muck Sample Lifted to Weigh Scales

FIG. 4-4. Muck Sample Weighed

4. Steps 1 through 3 were repeated until a consistent pair of readings was obtained for each specific muck and Syntron setting.

4.3 CALIBRATION DATA

Three aggregate mixtures were selected for the calibration procedure: minus 1/2 in. crusher fines, minus 3/4 in. road base and minus 1-1/2in. road base. Five test sequences were performed with these mixtures, as indicated in Fig. 4-5. The figure records the relationships measured for muck throughput rates determined for the range of Syntron potentiometer settings.

The calibration curves tend to converge for higher settings and throughput rates, regardless of muck type or moisture content. For the aggregate mixtures studied in

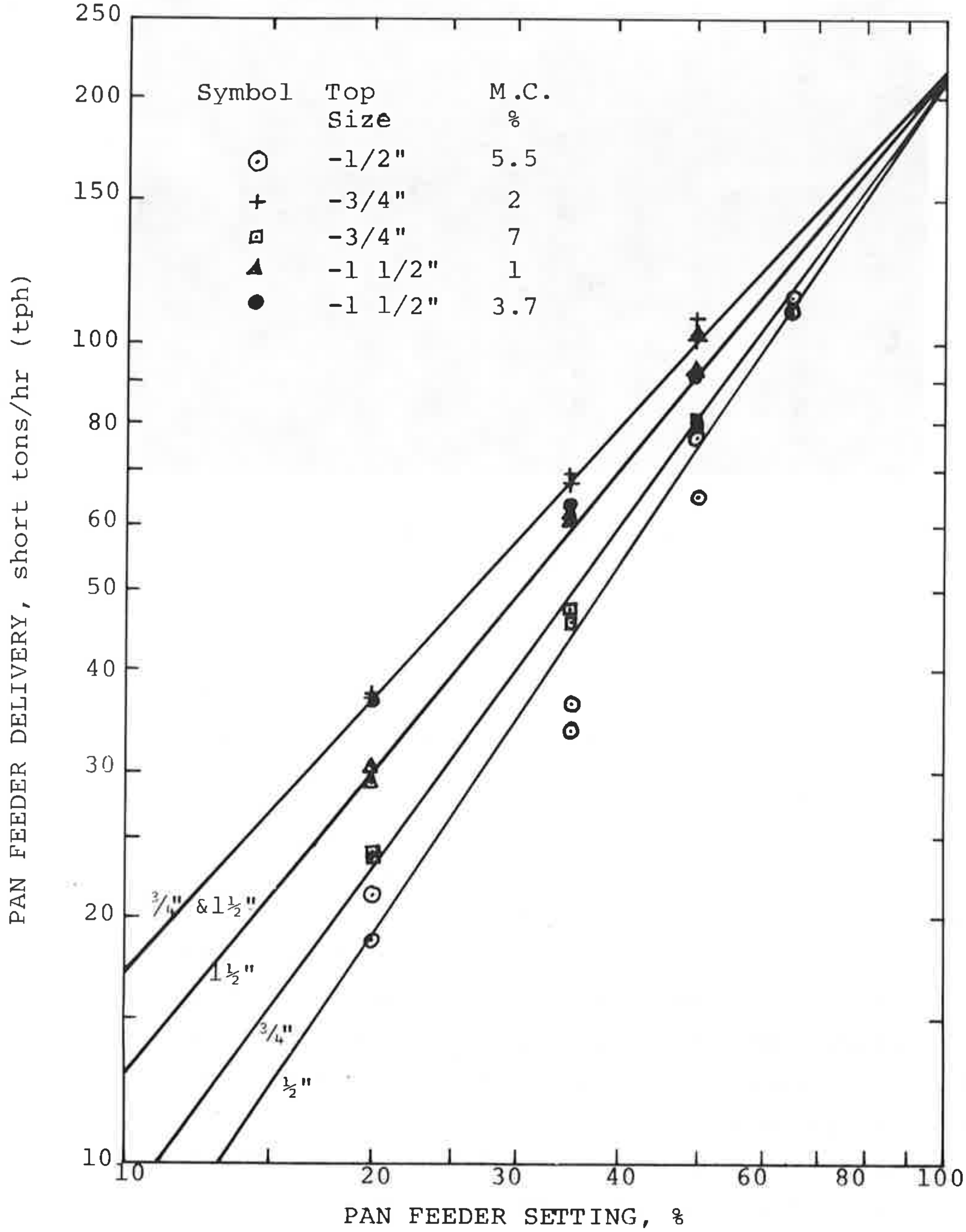


FIG. 4-5. Syntron Feeder Calibration

calibration tests, the rated throughput capacity of the pneumatic system of 100 tph was delivered by the vibratory feeder with control settings between 50 and 60 percent of full scale. The rated capacity of the Syntron F330 at the test installation was 110 tph.

Calibration data determined for different moisture contents indicate that the effects of moisture addition on the raw muck are complex. For coarser muck (e.g. minus 1-1/2 in. road base), added moisture tended to provide a lubricating effect on the feed. However, for finer muck (e.g. minus 3/4 in. road base), additional moisture tended to retard the feed by increasing the resistance to flow.

4.4 DISCUSSION OF CALIBRATION PROCEDURE

The method employed for system calibration was designed to measure throughput rates obtained under field operating conditions. In repeated determinations of muck rates for specific Syntron control settings, data obtained by this method were consistently reproducible, in spite of potential errors from several sources. Errors in calibration may have resulted from any of the following conditions:

1. With wet aggregate mixtures, a considerably longer period of operation was required for the depth of flow in the Syntron vibratory feeder to reach a steady state for each new control setting. In most cases, the first reading from each group of determinations was disregarded as non-representative.
2. At low feed rate control settings, flow of material from the surge hopper into the vibratory feeder was uneven, due to bridging and caving of material inside the hopper. The problem was observed feeding -1/2 in. material to the system, only, and was not significant at high feed rates.

3. Due to the configuration and position of the Radmark pipeline feeder, the portion of the diverting chute beneath the top of the Syntron trough was a relatively flat section. During the calibration tests, it was necessary to continuously clear the flat section of muck as it was delivered from the Syntron feeder. If allowed to accumulate in the upper portion of the chute, piled muck would tend to impede the flow of material from the lip of the feeder, leading to a lower apparent throughput rate than the true value. The chute was cleared manually, and at high feed rates it was sometimes difficult for the crew to keep pace with the flow from the feeder.
4. In operation during the capacity and wear tests, it was found that the Syntron vibratory feeder required adjustment for optimum performance. It may be expected that the relationship(s) determined between Syntron control settings and throughput rates were affected by changes in feeder performance.

4.5 POWER CONSUMPTION

Power consumption during the capacity tests was measured using three demand-kilowatt hour electric meters furnished by Public Service Company of Colorado (PSCo). See Fig. 4-5. The meters were installed to monitor power consumed by separate subsystems of the transport system. The individual components are identified as follows:

1. muck preparation unit, including double impactor crusher, vibratory screen and two conveyor belt drives.
2. feeder unit, including vibratory feeder and hydraulic drive for rotary pipeline feeder.
3. blower drive

FIG. 4-6. Three Electrical Meters and Power Factor Meter

The demand-kilowatt hour electric meters permitted measurements of peak demand and/or average demand over selected time intervals for each sub system. Test data were obtained as follows:

A. Peak demand was determined by timing the revolution of a calibrated wheel in the kilowatt-hour meters. Power consumption was determined for about one-minute intervals. Such readings were referred to as "instantaneous readings."

B. Average demand read directly from the meter for test purposes was taken over 15 minute intervals.

C. Public Service Company installed a magnetic tape recorder at the test installation to monitor power consumption for billing purposes. The recorder monitored power demand levels at 15-minute intervals, 24 hours-a-day, for the duration of the entire test program. These data were made available for data analysis and were used as a check on "B" above.

A comparison of data from "A" and "B" showed that peak and average demands varied about ±10%. The magnetic tape readings varied ±6% with the average demand readings.

The power factor (a measure of the efficiency of electrical power utilization, that is, the ratio of the demand to the available power) was measured by a separate meter installed at the site. Generally it showed that motor loads were relatively light. This measurement was of academic interest only in the capacity tests.

4.6 AIR VELOCITY PROFILES

Dilute phase conveyance by pneumatics requires high airstream velocities to keep the coarse, heavy solids saltating along the invert of the pipe or to keep the solids in suspension. Of interest is the minimum transport velocity below which solids begin to settle out, decrease the cross section of pipe and increase the local roughness due to bedload formation. Excessive bedload depths can eventually lead to a plugged pipeline unless sufficient power is available to resuspend the settled solids. The measurement of particle velocities can only be made with elaborate and expensive equipment. In this study it was possible only to measure the airstream velocities prior to feeding solids into the pipeline. By estimating slip velocities, particle velocities were calculated.

A series of air velocity profiles was taken at various intervals throughout the test program. A standard Pitot-static tube with an 8-in. long snout was inserted into a section of Schedule 40 mild steel pipe through a special fitting installed between pipe flanges which allowed rotation of the right-angled Pitot-static tube into a vertical traverse of the pipe's center-line. The Pitot-static tube had an outside diameter of 1/4 in. with a 3/32-in. diameter stagnation annulus. The peripheral static pressure ports were located 2-3/4 inches behind the stagnation port. The differential pressure measured between the stagnation and static ports was equivalent to the velocity head and was read on a water-air differential manometer. The manometer had a capacity of 8 inches water gauge. A coefficient of C_p=0.99 was assumed for the Pitot-static tube.

Appendix A lists the raw data and describes the computations necessary to develop the velocity profiles. These are shown in Fig. 4-6.

Velocity profiles give three pieces of information: the average velocity, the flow Reynolds number and hence flow regime, and pipewall roughness. However, the pressure drop is required before the pipewall roughness can be obtained. Fig. 4-6 compares the first and last velocity profiles taken for each pipeline configuration, inclined and horizontal. Several features can be observed:

a) The maximum velocity occurs above the pipe centerline in a consistent manner. This suggests that the soffit of the pipe might be smoother than the invert. Since the very first profile had been taken after aggregate had been blown through the pipeline, it is reasonable to expect that the finer solids carried in full suspension at high velocity "sandblasted" the upper part of the pipe. The coarser solids saltating along the invert (they could be easily heard bouncing and rolling on the invert) presumably did not provide a sandblasting effect. At the conclusion of the entire testing program, the smoothness of the pipe was examined by touch. The invert did feel somewhat smoother than the soffit but the difference was not marked. Also, a groove in the invert (6 o'clock position) verified the saltation flow regime pattern.

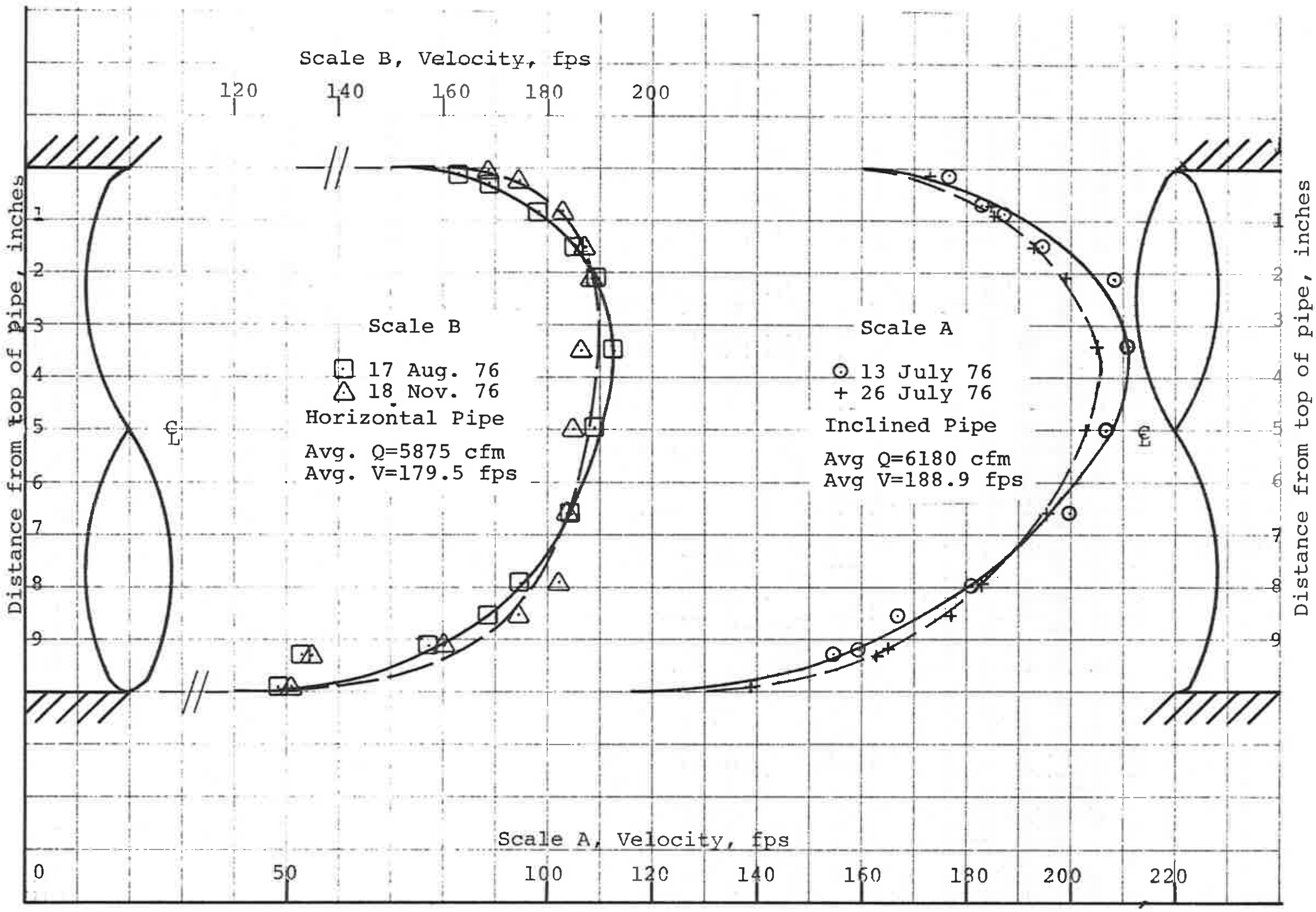


FIG. 4-7. Air Velocity Profiles

b) The airflow in the horizontal pipe configuration was reduced due to the additional headloss created by the presence of the four bends (two additional 90° elbows). The mean velocity dropped about 5% from that measured in the inclined configuration.

c) As time elapsed and total throughput of solids increased, the velocity profiles became slightly blunter; that is, the maximum and average velocities declined due to wear in the pipe increasing its cross section. Ovality of the pipe increased as the invert wore faster than the remainder of the pipe. Since the velocity traverses were made in the vertical or near-vertical plane only, and were "rotated symmetrically" in the computation of total airflow, the velocity profiles as shown are representative essentially for the vertical axis. The profiles measured in the horizontal pipe configuration were taken slightly off vertical (about 30°) to avoid the invert wear groove. The more symmetrical profile suggests that the invert wear is responsible for the asymmetrical profile in the inclined pipeline configuration.

d) The roughness of the pipewall cannot be determined because accurate pressure drop data were not available.

e) The flowrates were found by planimetering the area under the velocity profile and computing the volume of the profile rotated about its base, the cross-sectional area of the pipe. The Pitot-static tube positions were not chosen to give equal areas of pipe cross section due to tube fitting-interference so planimetry was necessary for computing flowrates.

f) The most notable observation was the high velocity required to transport coarse solids pneumatically. This single factor accounts for high energy consumption and high particle kinetic energies leading to high wear rates.

5. CAPACITY TESTS

Capacity tests were performed on the inclined pipeline configuration described in Section 2. The purpose was to determine the power required to transport varying sizes and quantities of tunnel muck simulated by aggregate with different moisture contents.

Five different sized mucks were produced for study in the capacity tests, as described in Section 3 - Muck Identification. System power requirements were studied in a sequence of ten different tests. Table 5-1 summarizes muck input conditions for the capacity test sequence.

TABLE 5-1. CAPACITY TEST SEQUENCE-VARIATIONS OF MUCK TYPE AND MOISTURE CONTENT

Test	Muck Type	Moisture Content (%)	Muck Designations
I-1	A	2.4	A-moist
I-2	A	4	A-wet
I-3	B	7	B-very wet
I-4	C	(NR)*	C-dry
I-5	C	(NR)	C-moist
I-6	D	3.7	D-moist
I-7	D	4.3	D-wet
I-8A	E	(NR)	E-moist
I-8B	E	0.9	E-dry
I-9	E	5.1	E-wet

*NR-Not Reported

The test procedure is described in Section 2.

Moisture content and muck size were varied more widely in the capacity tests than in the Syntron calibration tests described in Section 4. For this reason, it was necessary to interpolate and extrapolate additional calibration curves in order to determine throughput rates for all of the capacity test runs. Figure 5-1 indicates the best available estimates of the positions of supplementary calibration curves with respect to curves originally established from calibration test data.

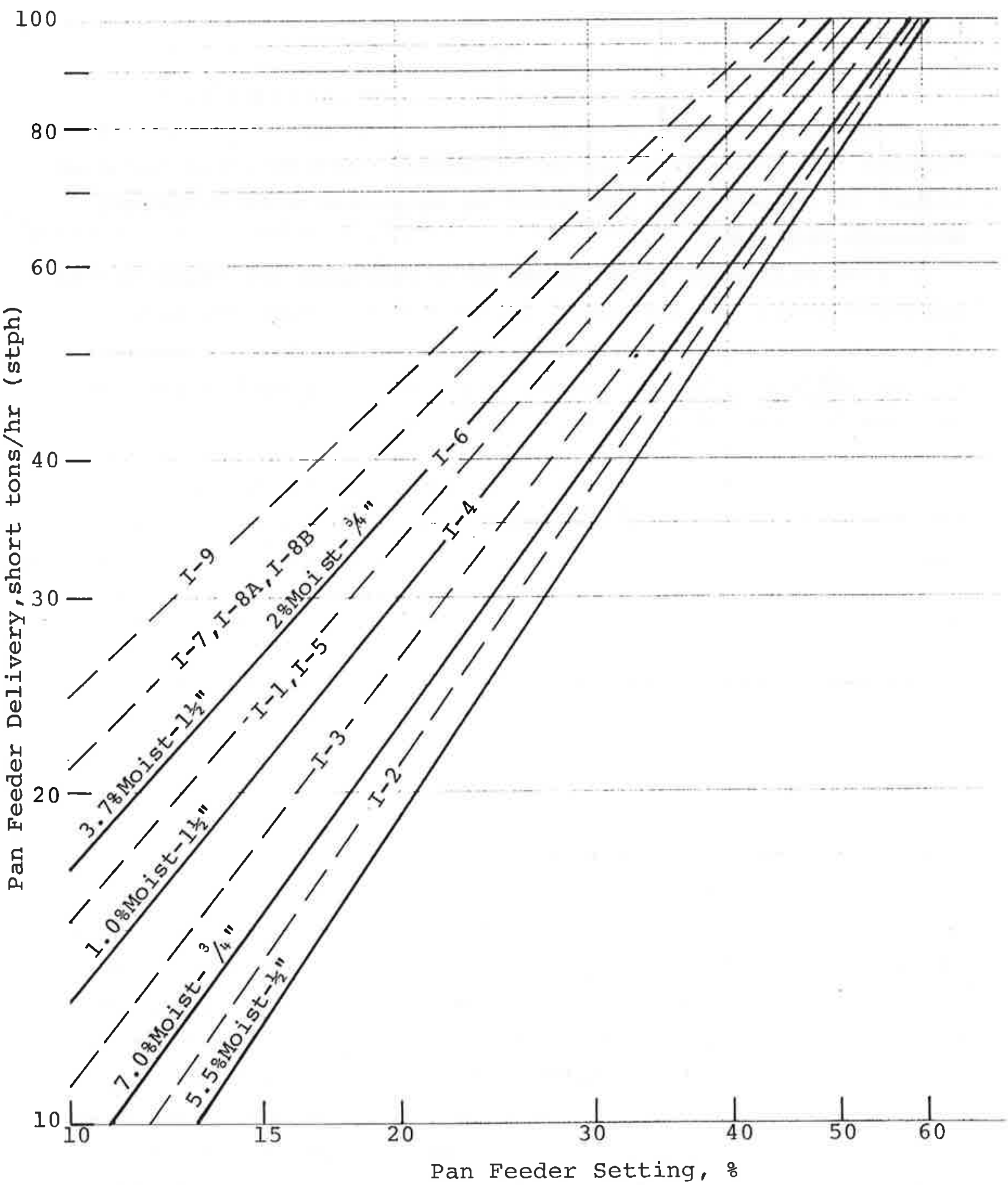


FIG. 5-1. Calibration Curves for Capacity Tests (Projected from Fig. 4-5.)

The capacity test data are listed in Appendix A along with the screen analyses obtained for these tests. The screen analyses for the wear tests are also included in Appendix B for convenience.

5.1 SCREEN ANALYSES

Screen size distributions were measured frequently because of the wide variations encountered in muck sizes. Bucket samples were collected as the aggregate dropped from the inclined conveyor belt into the surge hopper above the Syntron vibratory pan feeder. Some care had to be exercised in collecting samples because of the design of the muck preparation unit. After the front-end loader deposited aggregate onto the vibrating screen on the muck unit, the undersize fell immediately through onto the inclined belt. Thus, the fines were dropped into the surge hopper first. Meanwhile, the oversize material was conveyed to the crusher from which it discharged onto a horizontal slave belt connected to the long inclined belt. Although the impactor bars of the crusher were set as close as possible, the crusher did tend to discharge large stones (~1-1/2 to 2 in.). Thus, coarse muck followed fine muck on the inclined conveyor.

The sampler was instructed to collect a half bucket of fines and a half bucket of coarse in an attempt to average the sample size distribution. Once the muck was in the surge hopper, there was enough time and storage volume to desegregate the size distribution before muck fell into the Radmark feeder from the Syntron vibratory pan feeder. Unfortunately, space limitations above the Radmark feeder prevented any sampling there.

The screen analyses give a representative particle size in three ways: a weighted mean diameter, which the authors feel is the most representative; a d_{50} size; and a Rosin-Rammler intercept which is the particle size above which 36.8 percent of the solids by weight are coarser.

The Rosin-Rammler method, originated in 1933 for coal, appears to linearize solids distributions quite well (9).

It is based on a universal law of size distribution valid for all ground materials irrespective of the material and the method of grinding. It is given by

$$R_p = 100 \cdot e^{-(d/B)^M} \quad \text{.........................} \quad (5\text{-}1)$$

where R_p = percentage by weight of particles >d

d = particle size

B = size constant, determined by sieve opening on which 36.79 percent of the sample would be retained (intercept on ordinate of plotted equation)

M = distribution constant, the slope of the linear graphical plot.

For solids of uniform size, M is large (i.e., vertical slope). For a very wide size distribution, M is small (i.e., horizontal slope). Typically M has values between 0.5 and 1.5. The screen analyses in Appendix B favor the lower values of M indicating wide size distributions.

Referring again to the analyses in Appendix B, the coefficient of correlation is the ratio of standard deviation to weighted mean diameter. The coefficient of correlation R_p is a measure of the goodness of fit of the Rosin-Rammler equation. A perfect fit of the data gives a value for R_p of unity.

In general, the capacity tests were performed in order of increasing particle size. For each particle size, the tests were performed with increasing throughput in short tons per hour and with increasing moisture content. Muck size ranged from a weighted mean diameter of 2.9 mm to 12.2 mm, throughput from 0 to 100 tph, and moisture contents from less than 1 percent to 7 percent.

Figs. 5-2, 5-3, and 5-4, (photos) show various views of muck discharge from the deflector. Fig. 5-5 (photo) shows large rocks (up to 6 in.) of pink granite and black hornblende which have escaped the crusher and were blown through the pipeline. Note the absence of fines and the angularity of the discharged aggregate. The Radmark feeder had slot openings 4 inches wide. The rocks shown in the photo, being less than 4 inches wide, fell in with their long dimension parallel to the feeder slots.

FIG. 5-2. Discharge from Deflector (Side View)

FIG. 5-3. Discharge from Deflector (Top View)

FIG. 5-4. Discharge from Deflector (Side View)

FIG. 5-5. Collective Sample of Large Rocks Blown Through Pipeline

5.2 POWER CONSUMPTION

The measurement of the power required to operate the pneumatic pipeline haulage system was described in Section 4. The test data in Appendix B show the power requirements for each skid-mounted unit: the preparation unit, the feeder unit and blower unit. Typically, over the entire throughput range, the blower consumed 90 percent of the total power for the inclined pipeline configuration. The total horsepower is summarized for all three units and is converted to kilowatts per short ton per hour delivered over a distance of 1000 feet. This is defined as specific power and is a useful variable for computing power and hence costs to operate a pneumatic pipeline system.

The 15-minute power readings were used in computing the specific blower power. Figs. 5-6 through 5-9 show the relationship between specific blower power and throughput in short tons per hour for the inclined pipeline capacity tests. All ten curves show a decreasing specific power as throughput increases. The tendency for each of the curves is to level out at between 60 and 100 stph. This would appear to be the optimum specific power for the system because it represents the minimum amount of power required to transport a ton of muck. Unfortunately, more data points to the right of the optimum (at higher muck capacities) were not obtained due to automatic protective electrical shut offs on the Radmark feeder, Syntron pan feeder, and blower. These were installed by the manufacturers to prevent damage ultimately to the blower. Because the capacity tests were the first tests in the program, no effort was made to disconnect the protective devices. The equipment cut-offs were initiated when the air pressure downstream of the blower approached 11 to 12 psig. This pressure reading was upstream of the blower silencer, the return 180° elbow to bring the air pipe under the Radmark feeder, and the Radmark feeder. Thus, allowing for these losses, the Radmark feeder would leave a pressure drop much less than 12 psig to transport muck through the pipeline.

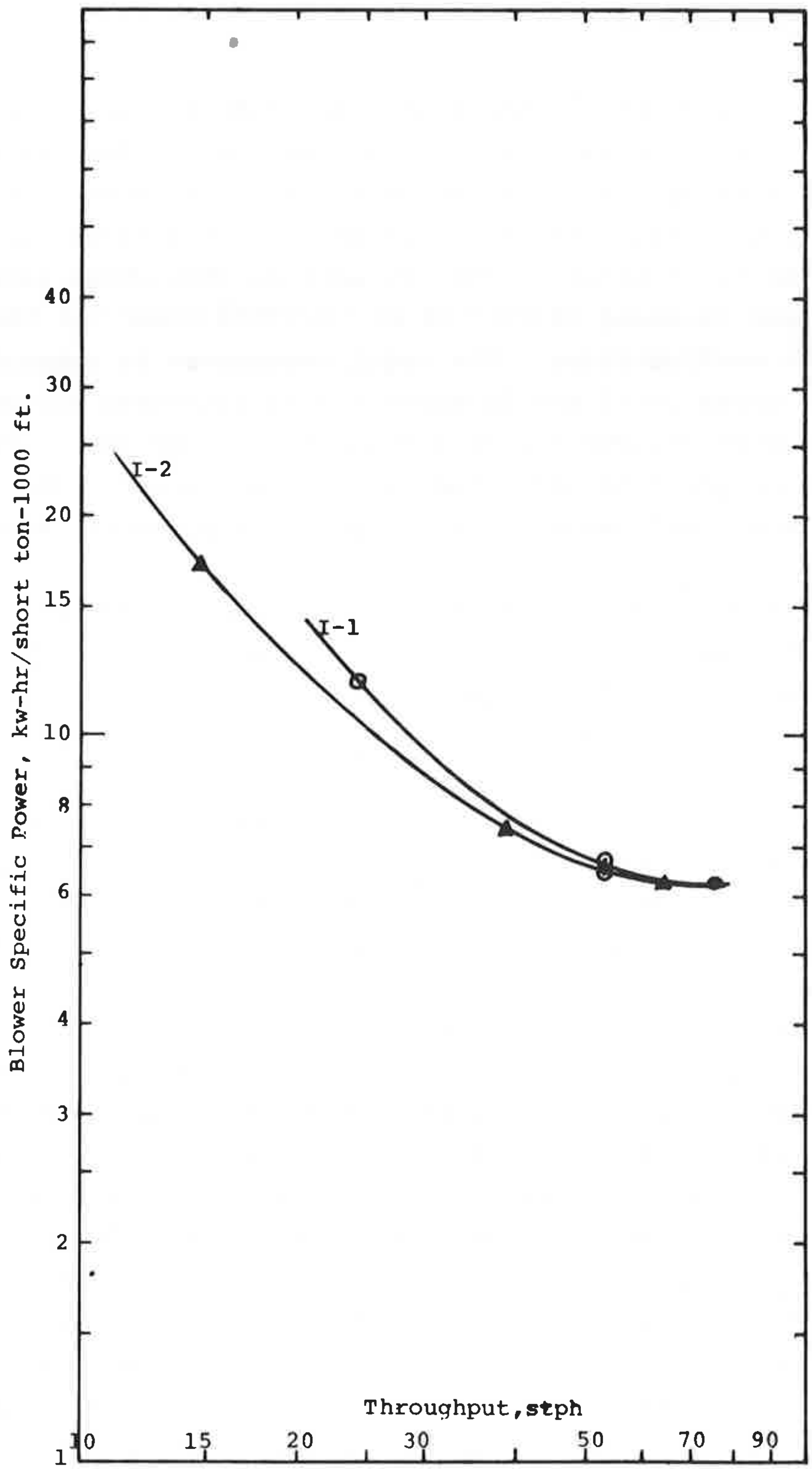


FIG. 5-6. Blower Specific Power vs Throughput, I-1 and I-2

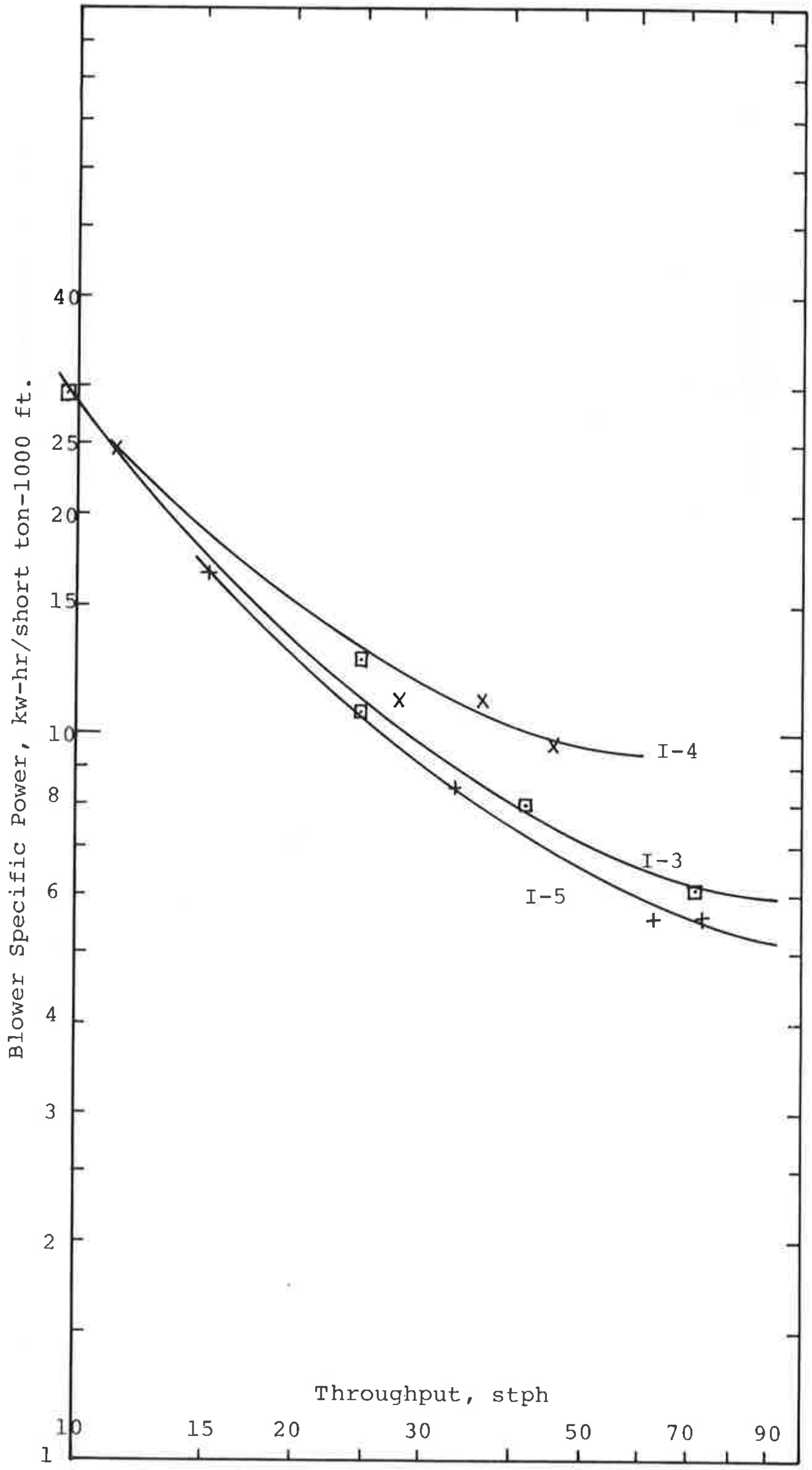


FIG. 5-7. Blower Specific Power vs Throughput, I-3, I-4, and I-5

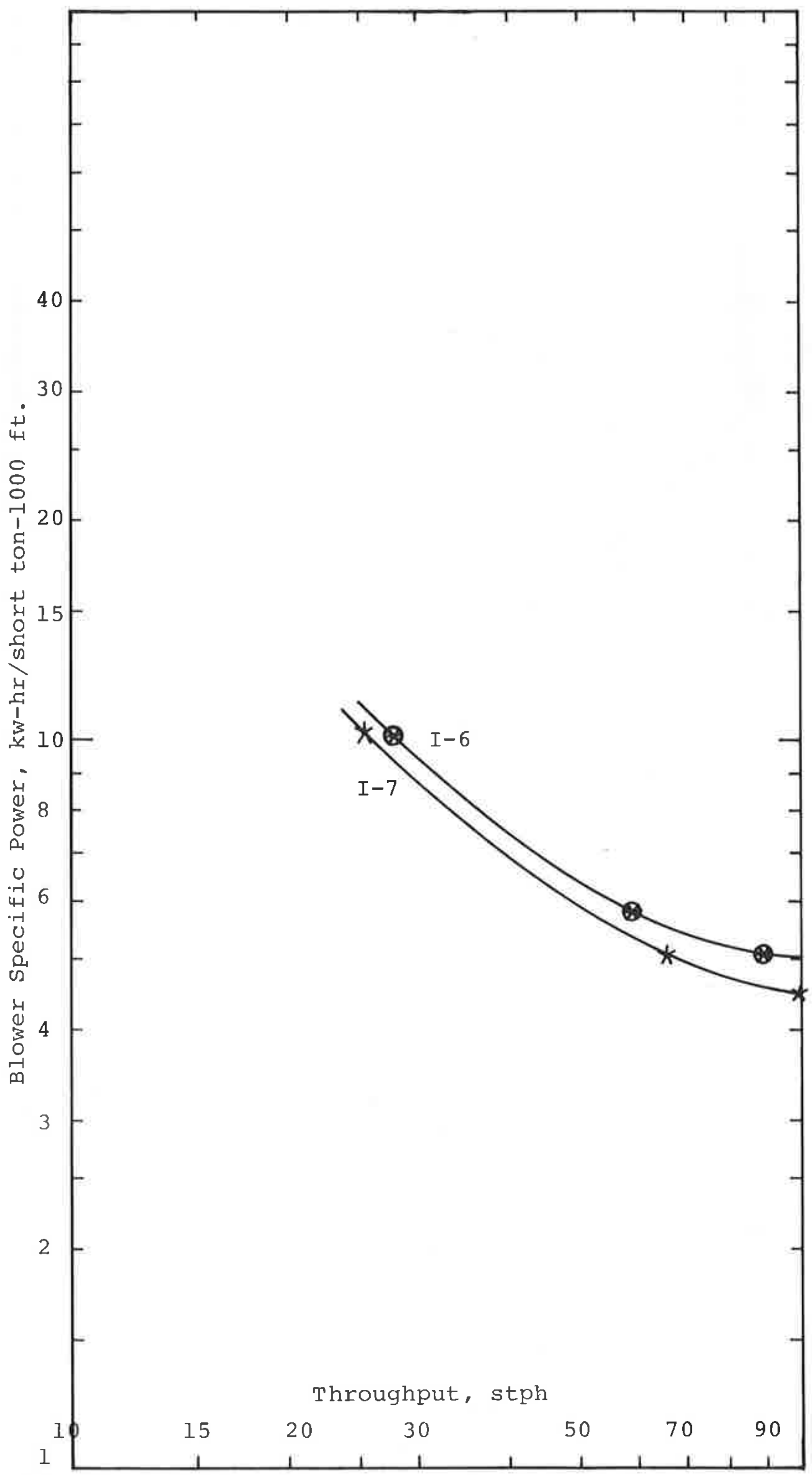


FIG. 5-8. Blower Specific Power vs Throughput, I-6 and I-7

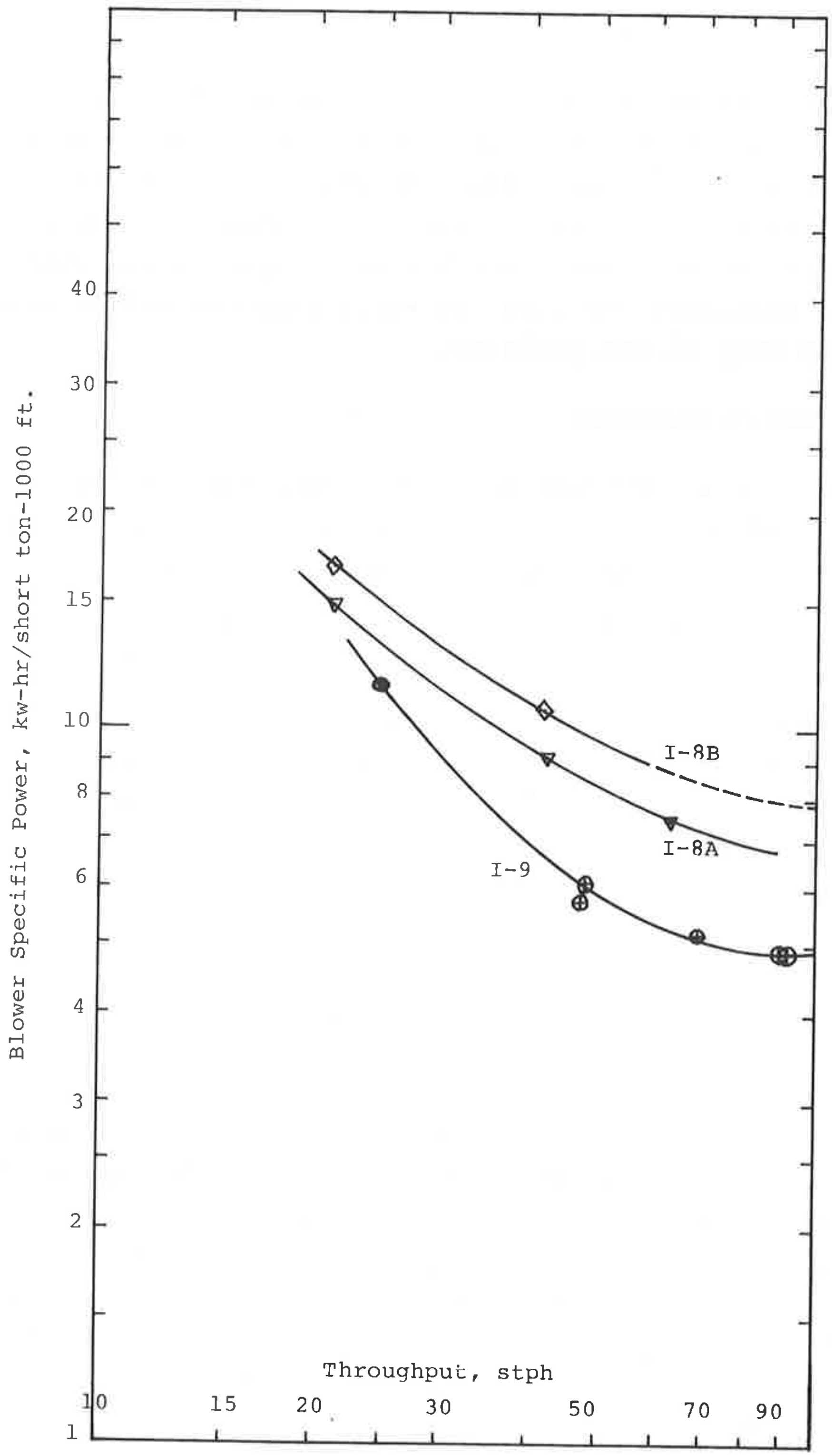


FIG. 5-9. Blower Specific Power vs Throughput, I-8A, I-8B, and I-9

If the throughput were increased beyond the optimum point, one would expect the specific blower power curve to increase until plugging occurred. Plugging could manifest itself in several ways: the Radmark feeder could choke, or the pipeline resistance could increase until blower capacity was inadequate to transport the muck, at which time the solids would come to a stop in the pipeline.

5.3 RESULTS AND CONCLUSIONS

The range of optimum specific powers encountered is:

Run No.	Specific Power, kw-hr/ton-1000 ft.	Throughput, tph	Avg WMD, mm	Moisture, %
I-4	max = 9.4	60	2.9-8.8	<1.0
I-7	min = 4.5	100	6.5-9.0	4.3

The virtual doubling of the specific power in these tests signals the sensitivity of a pneumatic pipeline system for muck haulage. The range of particle size and moisture content in these tests is probably realistic in terms of what might prevail in a tunnel excavation. Therefore, design flexibility must be regarded as highly important.

It must be noted that the calculations of specific power were scaled up to 1000 feet of pipeline for convenience, although the actual pipeline length was about 565 ft. Also, the pipeline contained 30^o and 60^o flatback elbows in non-horizontal configurations, and the pipeline alignment was "eye-ball precision." Ideally, specific power should be computed from a measurement of flow and pressure drop in a straight horizontal pipe under established (i.e., non-accelerating) flow. However, instrumentation was insufficient to permit this. Therefore, the specific power computed in this study was for a specific pipeline configuration, even though the pipeline was lengthened to 1000 feet.

From the data the following observations can be made:

a) The highest power requirements were by the coarser dry mucks (I-4 and I-8B) and the finer wet mucks (I-1,2,3).

b) The lowest power requirements were achieved by I-7 and I-9, both of which were coarse but with moisture contents of 4.3 and 5.1 percent, respectively. These were considered "wet" mucks. Thus, particle size does not seem to be as important as moisture content on specific power. Runs I-7 and I-9 have similar low specific powers and moisture contents but I-9 is coarser by almost 50 percent. Similarly, I-4 and I-8B are dry mucks with similar specific powers but I-8B is about one-third coarser. Fig. 5-9 shows a substantial variation in specific power for muck E having a weighted mean diameter range of 8.4 to 12.2 and a range of moisture content from less than 1 percent to 5.1 percent. This also demonstrates the importance of moisture. This fact is analagous to slurry pipelining theory which states that when the solids are coarse and heavy such that form drag predominates over skin friction drag, then power requirements for pipeline transportation tend to be fairly constant for a given throughput regardless of particle size.

c) Certain site conditions must be considered. Muck throughput is decreased as the ambient air temperature increases because the viscosity of air increases. An increase in relative humidity increases the density of the air thereby increasing the power requirements for the transportation of fine muck but possibly decreasing the power requirements for coarse muck when the moist air is able to support coarser muck in suspension and reduce particle-wall friction. The altitude of the test site was about 6000 ft. which accounts for a reduction in the density of air by about 20 percent, from sea level, and which requires a derating of the blower for a specific throughput.

d) Excessive moisture can cause caking of fines in the Syntron pan feeder, the Radmark feeder, and pipeline thereby increasing power requirements. The amount of moisture considered beneficial for pneumatic transportation must be related to that which delineates lubrication of the solids from cohesion of the solids by surface tension effects.

6. WEAR TESTS

This section deals with patterns and extent of wear in various components of the system, particularly with respect to the bends or elbows and their liners. The elbows wore more quickly and needed more attention than any other component in the system, and therefore yielded more data. Developed data consist mainly of photographs, mineralogical analyses, size analyses of the conveyed material, and an analysis of the liner material in the bends. Working drawings from the system's manufacturer and locally drawn sketches provide the geometrical characteristics of the bends for presentation of wear patterns. Wear was encountered in three phases of operation:

a. Capacity Tests (uphill pipeline) through July, 1976.

b. Wear Test (horizontal pipeline) through November, 1976.

c. Wear Test (horizontal pipeline) through August, 1977.

6.1 ELBOW WEAR - 1976 TESTS

There were two pipeline layouts which were used during these tests. The first layout used through July 19, 1976 was run uphill to a discharge point. See Chapter 2. In the capacity tests, two elbows were involved, a 30° flatback bend at the bottom of the hill and a 60° flatback bend at the top of the hill. The term "flatback" simply means that the elbow or bend has a rectangular cross section instead of circular. The advantage of this design is to localize the wear on liner plates and allow easy changeability of the liners.

Approximately 450 tons of aggregate were blown through the pipeline in the uphill configuration. The mineralogical analysis of conveyed material is given in Chapter 3.

Five types of muck were put through the system: A-1/2 in., B-3/4in., C-1in., D-1.5in., and E a combination of -1.5in. and -3in., muck. The coarser muck was crushed in amounts depending on the mesh size of the vibrating screen.

For a size analysis of the five types of muck, see Appendix B. Few wear measurements or photographs were taken early in this part of the program which was devoted primarily to capacity tests. Moisture content was not controlled in these tests because water was unavailable at the time.

The total throughput of muck for each test series is, therefore, the main tool for description of wear, along with the fact that the majority of the flowing muck covers approximately 1/6 of the bottom of the pipe in a sliding regime when the pipe is in a horizontal configuration. This sliding regime could be observed at the pipeline discharge and heard as it flowed in the pipes. The 30^{o} bend did experience liner wear-through so it was replaced and the other worn liners were rotated and resequenced. The 60^{o} liners did not wear through, and the liners showed more uniformly distributed wear than did the 30^{o} liners. The 60^{o} liners were also rotated and resequenced (but were not replaced) during the inclined pipeline tests.

The second layout resembled a loop and facilitated reuse of conveyed material. This loop contained four bends: the 30^{o} Radmark flatback elbow, a 90^{o} Esser bend, a 90^{o} Radmark flatback elbow (see Figs. 6-1, 6-2), and the 60^{o} Radmark flatback elbow. All bends were laid on an essentially horizontal plane. Approximately 400 tons of material were conveyed in this configuration.

The wear in the Radmark 30^{o}, 60^{o}, and 90^{o} flatback bends was analyzed with the aid of drawings to show primary and secondary impact points for comparing actual and theoretical wear. The theoretical primary impact point is the intersection of the projected bottom center-line of the upstream straight pipe with the bottom of the sidewall surface of a liner in the flatback bend. This primary impact always occurred in the fourth liner in each of the bends because of their nearly common bend radius. It was assumed that the angle of incidence equals the angle of reflection for a rock hitting the liner. Thus,

FIG. 6-1. Five-Segment Esser Hardened Steel 90° Bend (Flow: Right to Left)

FIG. 6-2. Radmark 90° Flatback Bend with Wear Liners (Flow: Background to Foreground)

the secondary and tertiary impact points were easily plotted as shown in Figs. 6-3 and 6-4. In comparing theoretical wear points to observed wear, this is not entirely what happens. The observed wear agrees only with the theoretical wear zone for the primary impact zone, but not for the remaining impact zones. This difference is attributable to two factors: the width of the muck stream and particle interference. A detailed explanation follows:

1. On the 90° Radmark bend, the radius of curvature is smaller so the impact zones do not match those of the 30° bend or 60° bend. (The 30° bend and the first half of the 60° bend are identical.) The theoretical impact zones show the primary impact zone to be just on liner 4 downstream, a secondary rebound on the inside bend and a tertiary impact on liner 9. Observations however, showed secondary impact zones in liners 6, 8 and 10. See Fig. 6-5 (photo). The reason for very little wear on liner 9 and dished gouges on liners 8 and 10 is shown in Fig. 6-3. The extreme width of muck stream rebounds from liner 3 and impacts liners 7 and 8, and the rebound from the downstream portion of liner 4 impacts liner 10; neither of these two rebounds contact the inside radius of the bend. The primary impact point on liner 4 causes rebound to impact against the inside of the bend, as seen in Fig. 6-3, but being a curved surface, this tends to disperse the rebounding particles so that they do not concentrate at a point on liner 9, but are more evenly distributed over 8, 9, and 10. As wear in the liners increases in the primary impact area, rebound from liner 3 and downstream portion of liner 4 moves downstream on liners 8 and 10 respectively adding to the dished look of liners 8 and 10. As a gouge forms at the primary impact point on liner 4, the angle of reflection from this point becomes steeper and muck impacts the inside of the bend progressively upstream as

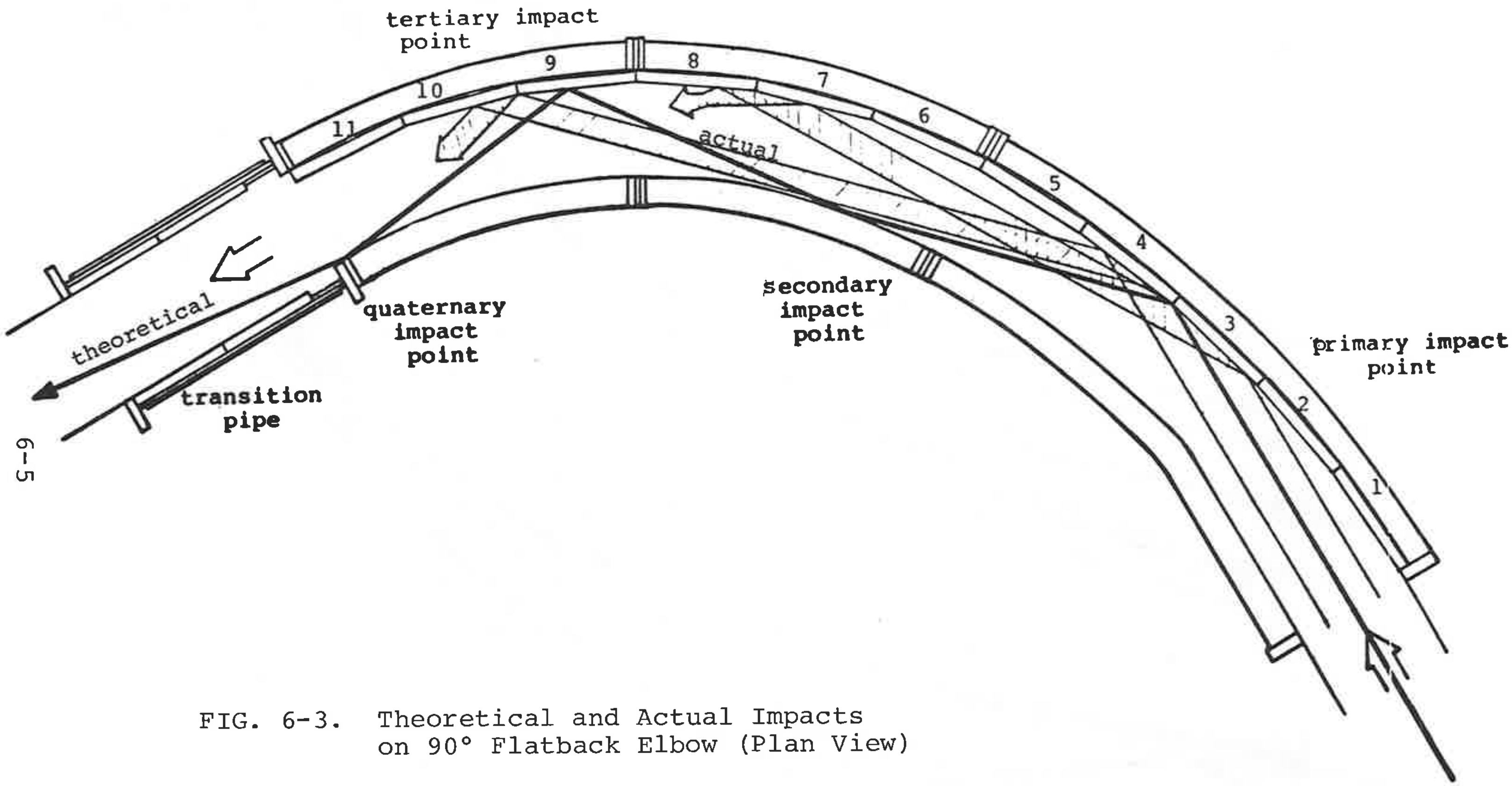


FIG. 6-3. Theoretical and Actual Impacts on 90° Flatback Elbow (Plan View)

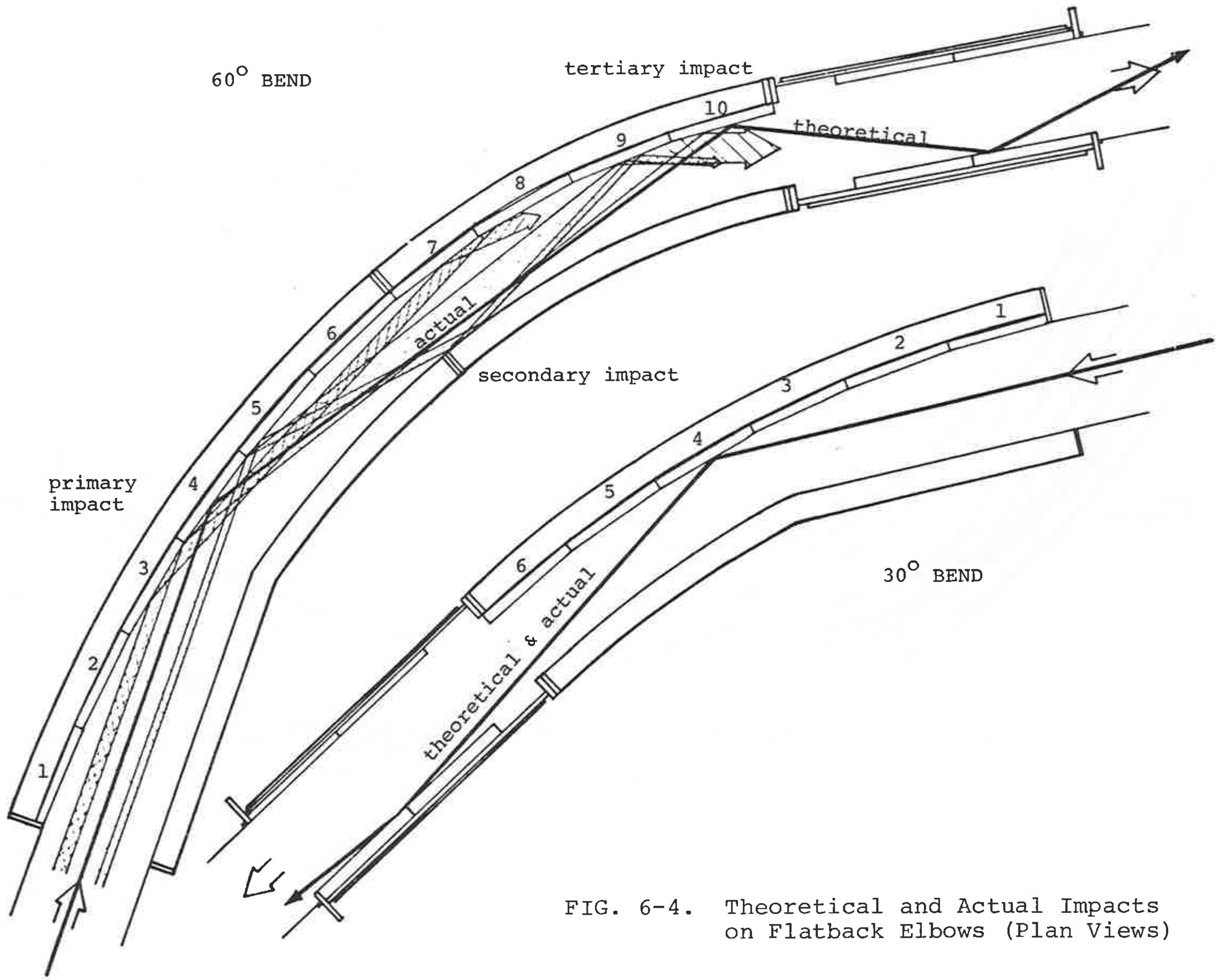


FIG. 6-4. Theoretical and Actual Impacts on Flatback Elbows (Plan Views)

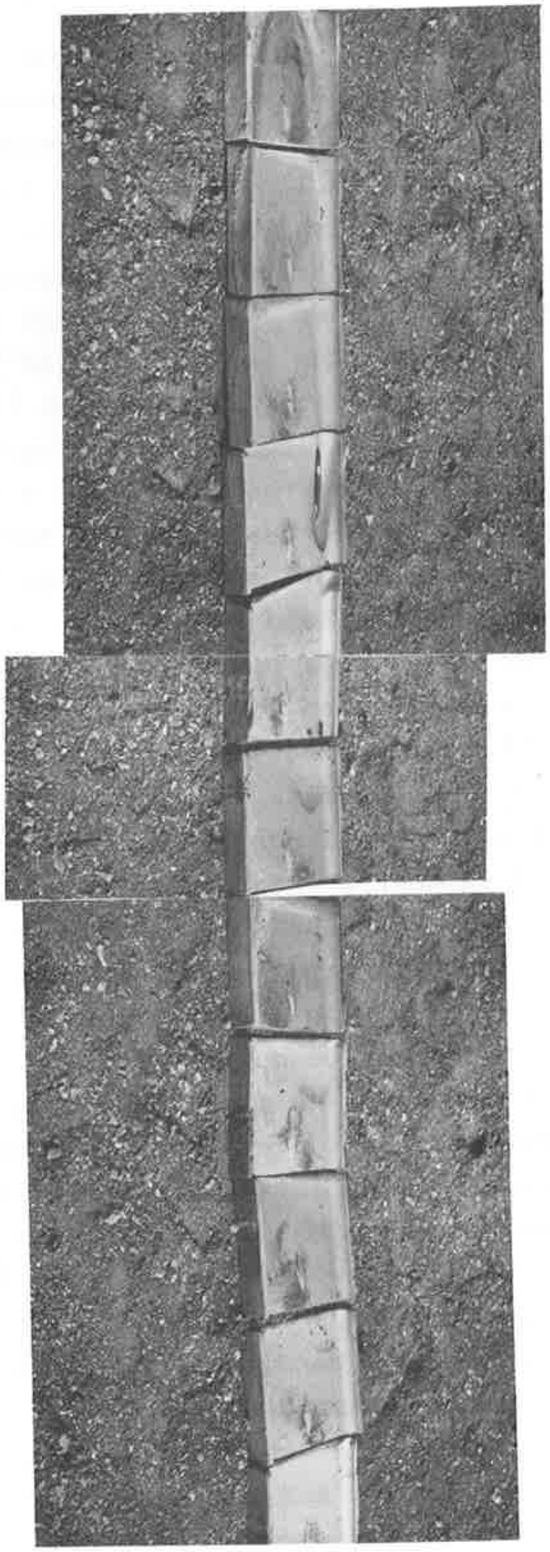


FIG. 6-5. Composite Inverted Wear Photos of 90^{O} Flatback Bend (Flow Right to Left, Wear on Bottom Edge of Liners)

the gouge grows deeper. The gouge normally is localized; but as it grows deeper, this gouge influences the rebound of progressively more muck. The manifestation of this phenomenon is evident in liner 6. Muck leaving the gouge in liner 4 impacts the inside curve of the bend closer upstream and then rebounds to impact liner 6. A gouge must form in liner 4 in order for severe wear to occur on liner 6. The inside curve of the bend is also worn once a major gouge is formed on liner 4, but its severity is mitigated by centrifugal forces acting on the flow stream toward the outside of the bend.

2. In the 60° Radmark bend, theoretically, the primary impact occurs on liner 4, and secondary impacts occur on the inside curve of the bend and on liner 10. (See Fig. 6-4.) The actual wear pattern, Fig. 6-6(photo), shows the primary impact zone on liner 4 and secondary impacts on liners 8 and 10. The explanation for this is similar to the analysis for the Radmark 90° flatback bend. Impacts from the muck stream on liner 3 rebound to impact liners 7 and 8, and as wear increases, this rebound moves onto liner 8 almost entirely. Rebounds from liner 4 impact liner 10, some after hitting the inside curve, and some without hitting it. Rebounds from liner 5 impact liner 10 after impacting the inside curve. As wear increases, and gouging occurs in liner 4, muck is focused by liners 4 and 5 to impact the inside curve of the bend within inches downstream of the first 30° segment of the bend. This point actually wore through during the first wear test and had to be patch-welded. See Fig. 6-7.
3. The 30° Radmark bend is identical to the first 30° segment of the Radmark 60° bend. All rebounds from this bend impact on the transition cone liners in theory and in actuality. During the wear test of 1976, two types of liners were used, Nihard and D2S, a high chrome steel. The composition of each is listed in Table 6-1.

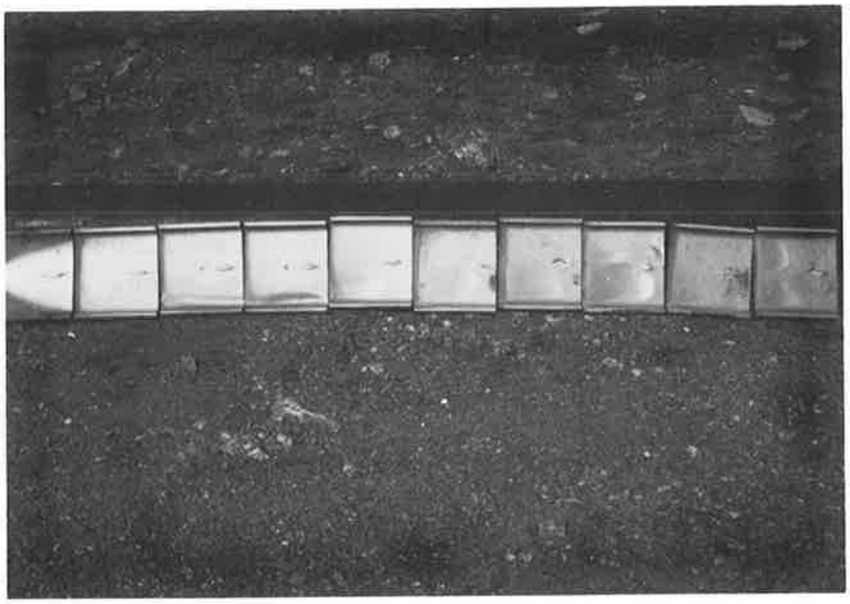


FIG. 6-6. Wear in 60° Flatback Bend (Flow Left to Right)

FIG. 6-7. 60° Flatback Bend with Lower Outside Hole Worn Through Liner and Inside Upper Rebound Hole (Patched)

Note: Two liners downstream of perforated liner had been rotated 180° previously.

TABLE 6-1. LINER BRICK MATERIAL
(typical analysis)

Nihard	D2S
C-3%	C-1.5%
Mn-0.6%	Mn-0.50%
Si-0.85%	Si-0.30%
Ni-4.2%	Cr-11.50%
Cr-1.5%	Mo-0.80%
typical hardness +50 Rockwell C	V-0.85%
	S-0.10%
	typical hardness 58/60 Rockwell C

During the test of the Nihard liners, approximately 540 tons of material were put through the system, 450 of these tons conveyed in the uphill configuration of July 76 and the remainder conveyed in the horizontal configuration prior to Aug. 19, 1976. Liner 4 in the 30^{o} bend had a hole (1 in.x1/2 in.) by the end of July after 450 tons of throughput. Of the 450 tons of material put through the system which wore out this liner, 80 tons or 18 percent were muck "A", 46 tons or 10 percent were muck "B", 74 tons or 16 percent were muck "C", 92 tons or 20 percent were muck "D", and 158 tons or 35 percent were muck "E". Between the end of the July run and August 10 the liners were rearranged to take the badly worn liners out of the severest wear areas.

Two hundred and seventy tons of muck D were run after August 19, 1976. At this time, the D2S liners were in the system. Fig. 6-8 (photo) shows liner 4 in the 30^{o} bend (with pen) which, although not worn through, probably would not have survived 450 tons of throughput.

Since the D2S alloy steel liners cost almost double that of the Nihard liners, there appears to be no advantage in using D2S liners based upon this series of tests.

4. Esser Elbows - 1976 Tests

The Esser 90^{o} circular elbow carried 400 tons of muck during the last half of 1976 when the configuration of the pipeline was made horizontal. Slight gouging was noted at the 9 o'clock position looking upstream from the downstream end of the first 30^{o} segment (Fig. 6-9, photo). This gouging continued across the connec-

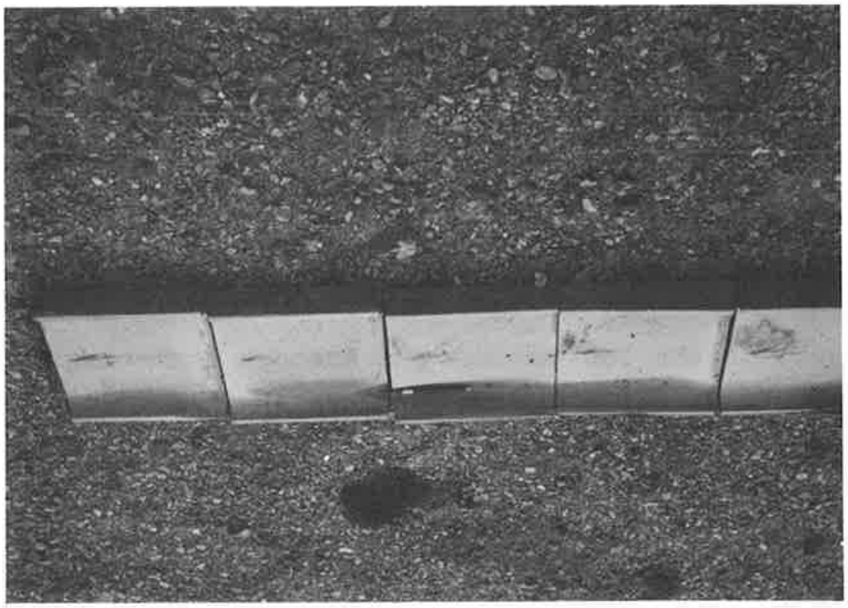


FIG. 6-8. Inverted Photo of Wear in 30° Flatback Bend (Flow Right to Left, Wear on Bottom Edge, First Liner not Shown)

FIG. 6-9. Wear in First Segment of 90° Circular Bend (Looking Upstream)

tion between the first 30° segment into the second 30° segment. During the tests, the first and second segments were interchanged subjecting each in turn to a severe impact. The third 30° segment was not subjected to the severe gouging of the first or second locations. The elbow liners were not worn through at the end of this test period.

6.2 DISCUSSION

I. Because of the low tonnage put through these segments (400 tons), it is difficult to conclude at this point that the Esser 90° bend is better than the 90° flatback elbow. There is, however, less concentration of wear in the Esser bend than in the Radmark bend, which speaks well of the geometry of the bend. There is also no sudden enlargement to the fluid/solid flow which occurs in the flatback bends. The conveyed muck appears to be picked up off the bottom of the pipe by the round liners, and then spiraled through at least 180° of rotation, judging from the observed wear patterns.

II. In comparing the Radmark flatback bend with the Esser bend, the following points must be considered:

   A. Muck was not fully accelerated when it encountered the Radmark 90° flatback bend. The distance between the point of intersections of the two bends was 90 ft. Calculations suggest that this distance is insufficient to develop terminal velocity for coarse muck.

   B. Muck was fully accelerated when it reached the Radmark 30° and 60° bends.

   C. Wear life of a horizontal Radmark bend is governed by the most severe impact portion of the bend (e.g., liner 4). A maximum of 450 tons throughput can be achieved if Nihard liners are used. The expected liner life may by assumed to be 300 tons throughput of coarse muck or about 7-1/2 hours at 40 tons per hour throughput. At the 300 ton point the system should be shut down, and the liners sequenced or rotated to place worn liners in less severe impact areas.

D. As will be shown shortly, the Esser bend can be left unattended in excess of 19 hours in the horizontal configuration. At approximately 20 hours of operation at 40 tph the segments of the Esser bend must be rotated requiring a system shutdown.

E. Experience at this site has shown that the covers can be removed, liners replaced, and covers replaced by two men within 25 minutes on the Radmark 30° bend. The Radmark 90° bend requires approximately 45 minutes for the same operation. These times are considered excessive because of the poor design. Better cover designs must be developed to ensure easy accessibility and less air leakage.

F. To unbolt, remove/rotate, and rebolt any two adjacent Esser bend segments will require at least two men with appropriate levers or jacks and approximately 2 hours of work if the bends are lying on the ground. Several men or a hoist will be required if the segments must be lifted into position. When working in cramped quarters, the Esser bends can be labor intensive.

G. A "spare" Esser segment is normally required when a liner has worn out and requires replacement. The spare is rolled in to replace the segment containing the worn out liner. The removed segment must be taken to a shop area where the segment liners are heated with a torch to melt the tar which holds the liner in place. Worn liners are then pulled out and new ones inserted. New tar or plaster is added as needed to secure the liner in place. The time and labor involved in transportation to and from the pipe line and in the relining process must be considered when comparing the advantages of the Esser elbows.

H. Experience has also shown that lead time for orders from the Esser company in Germany can be many months and substantial shipping and entry duties are incurred.

I. It is seen from this study however, that the Esser bend will stay in the system unattended for almost three times the length of time required for maintaining the Radmark flatback bend.

J. The circular geometry of the Esser bend liner does distribute wear over a larger area than does the Radmark flatback bend liner in any configuration including vertical.

III. With regard to wear severity:

From calculations, it is apparent that it will take greater than 100 feet to accelerate particles larger than 1/2 inch in diameter to terminal velocity when this system is under heavy load. In observing the pipe layout, it is seen that there are only 90 feet between the center-lines of the west headed and the east headed pipeline. This will leave approximately 85 feet between the end of the Esser 90° bend and the initial impact point in the Radmark flatback 90° bend. Therefore, the kinetic energy of particles will be less than its original value as particles leave the Esser 90° bend with particle interference. The kinetic energy of the particles varies with the square of the velocity and directly with particle mass so it would be expected that the Radmark 90° bend would experience less severe wear than any of the other bends. This was verified during the actual tests. No liners in the Radmark 90° flatback bend wore through during any of the tests in 1976 or 1977 while several liners in the Radmark 30° and 60° flatback bends did wear through. Liners in the three Radmark bends had been in the system for the same length of time during each portion of the test. When describing the kinetic energy of particles flowing through the pipe, the progressively higher velocities in the pipeline, due to expansion of the air and lower pressures encountered as the particles travel downstream, are assumed to compensate for the particle attrition/mass reduction due to impacts with the bend liners.

Particles impacting the Esser 90° bend and the Radmark flatback 30° and 60° bends are assumed to be at their terminal velocity. Particles impacting the Radmark 30° flatback bend are at their terminal velocity because of the two acceleration zones caused by the 8-inch diameter pipe within the telescopes preceding this bend.

6.3 MISCELLANEOUS WEAR

A. Pipe wear (Mild Steel-Schedule 40)

Micrometer measurements were taken July 30, 1976, on a Schedule 40 mild steel pipe two incles into the pipe. This was pipe Sec. #1 shown in Fig. 2-2. The results are listed below:

	(Schedule 40 pipe),West in.	(Schedule 40 pipe),East in.
12-6 o'clock	10.0775	10.0554
3-9 o'clock	10.0323	10.0071
1-7 o'clock	10.1115	10.0518
11-5 o'clock	10.0119	10.0501
2-8 o'clock	10.1100	10.0409.

The initial inside diameter of the pipes was 10.010 ±0.01 inches as measured before the start of the test. It is apparent that the majority of the wear occurred at the 1-7 o'clock position on the west Schedule 40 pipe and at the 12-6 o'clock position on the east Schedule 40 pipe. On listening to the flow of particles in the pipe and observing the particles discharge from a straight pipe section, it can be concluded that the above wear was concentrated at the bottom of the pipe in the 6 o'clock position. The original wall thickness was 0.365 inches. At the time of the above measurement, 450 tons of material had been run through these pipes. Life of the west Schedule 40 pipe, had it continued to remain in service without rotation, may have been expected to be

$$\frac{10.365-10.010}{10.1115-10.010} \times 450 \simeq 1600 \text{ tons before holing through.}$$

B. 10"x8" Transition wear

The two telescopes were constructed of 8-in. diameter pipe placed concentrically within a 10-in. diameter pipe. Each telescope required a transition reduction from the 10-in. pipe preceding to the 8-in. pipe within the telescope. During the 1976 testing, each of these transitions was repaired once. The downstream transition contained a liner, but this was not replaced during the 1976 testing. After 2 hours and 40 minutes (approximately 100 tons of throughput) of testing in 1977, both transitions failed almost simultaneously along the bottom near the downstream flange. See Figure 6-10 (photo). Both were removed and repaired. The upstream (unlined) transition was given a 1/4 in. cladding of mild steel over the entire outside, and the downstream (lined) transition was patched on the outside and relined on the inside. Having been repaired, both transitions continued in service through the remainder of the 1977 test (660 tons of throughput).

Longer reducers (about two feet in length) with liners are recommended to increase wear life.

C. Discharge deflector

The discharge deflector contained a hardened cone liner to help direct the flow. The liner was a Meehanite "Almamite" type WS which is a martensitic iron with free carbon in modular form. Brinell hardness ranges from 400 to 525. The discharge deflector had seen service prior to this test, and it was not known how much of its useful life remained. See Fig. 6-11 (photo). The discharge deflector liner cone and casing were worn through during the 1976 testing prior to having reached 400 tons of throughput. The hole occurred in the bottom of the discharge cone where the bottom centerline of the upstream pipe intersected the cone surface. See Figs. 6-12, 13 (photos). The cone was then patched and rotated, and continued in service. This discharge deflector was not used in 1977.

FIG. 6-10. Invert Wear on 10"x8" Reducer Between Telescopes

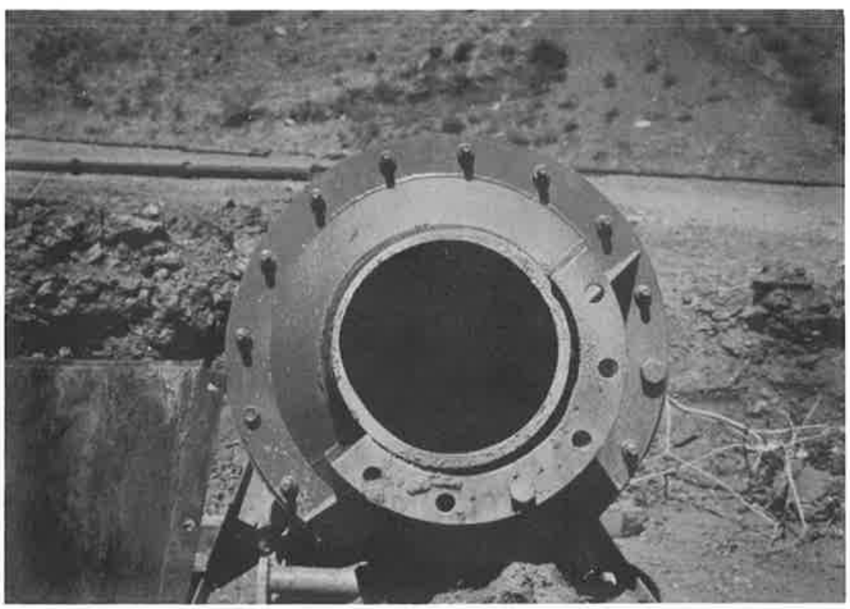


FIG. 6-11. Deflector Without Top Cover Showing Previous Liner Wear (10 o'clock)

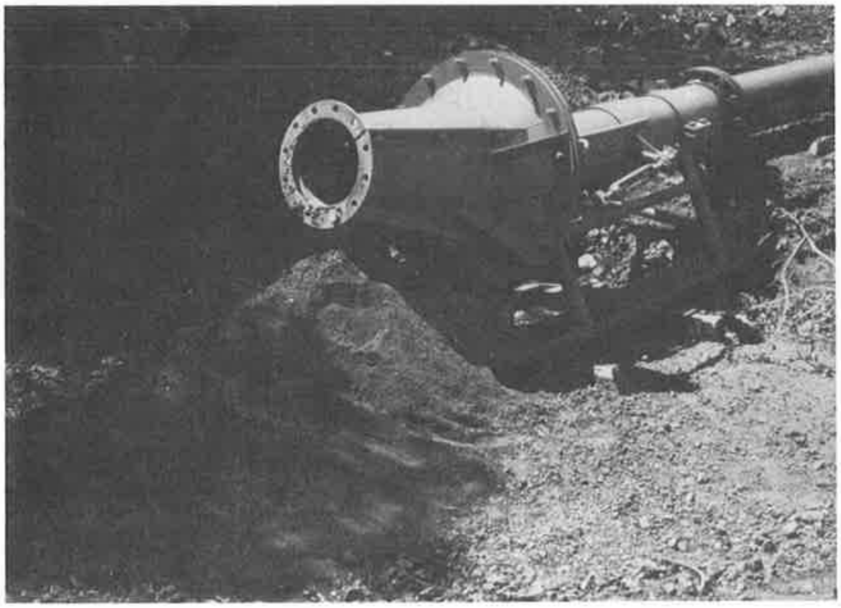


FIG. 6-12. Deflector Raised for Maximum Trajectory
(Note Fines Leaking from Hole in Deflector)

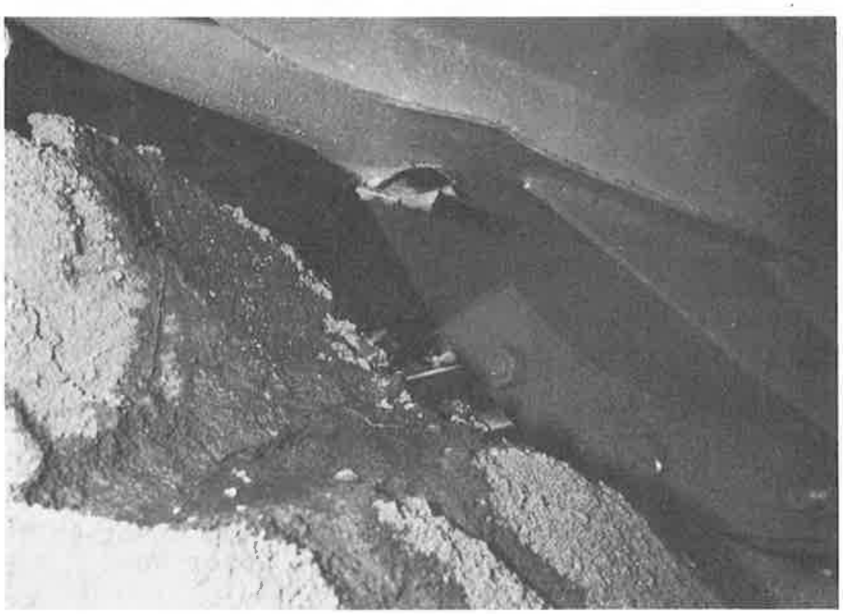


FIG. 6-13. Hole Punched Through Deflector Bottom

D. Esser Pipe

No appreciable wear was detected on the Esser hardened steel pipe other than a narrow (<1 in.) groove in the invert. It was not measured after the 1976 wear tests.

6.4 1977 WEAR TEST

The wear test of 1977 incorporated some modifications to the horizontal pipeline configuration. The 60° flatback bend was replaced by a Radmark 90° circular bend. This new bend was not evaluated for this test program but it did last the 19 hours of wear testing. The 60° flatback bend was replaced because there were insufficient unworn liners to accomodate it in the wear test program. Thus, only the 30° and 90° flatback bends and the Esser 90° circular bend were compared in the final test program.

The new 90° circular bend would have placed the discharge point just west of the hillside slot. Therefore, additional pipe was required in the south leg of the pipeloop. Sections of Schedule 40 mild steel pipe were placed both upstream and downstream of the new 90° circular bend. This extended the south leg of the pipeloop to permit discharge into the slot cut into the hillside. The downstream section of mild steel pipe was to straighten the flow prior to its entering a 20-ft. section of ceramic-lined fiberglass pipe. This pipe was supplied by Fiberglass Resources Corp. of Farmingdale, Long Island, NY. It contained 4-in. ceramic tiles cemented in a diagonal pattern (at 45° to the central axis of the pipe) onto a fiberglass pipe by an epoxy resin. Tile coverage was in excess of 99 percent. The discharge deflector was removed and flow from this pipe discharged into the hillside.

The 1977 wear test attempted to gain more information on different materials for wear life in the bends. The tests were broken into two 5-hour increments and one 9-hour increment of run time. At the end of each increment of run, liners were removed from the Radmark flatback bends, weighed, and photographed. An extensive collection of photographs is on file in the Basic Engineering Department of the Colorado School of Mines.

The muck selected for the 1977 wear tests was minus 3/4 in. aggregate. The screen size on the vibrating screen was 1 inch. Since the goal was to run for as long a period as feasible, it was decided to keep the muck size small in order to minimize use of the crusher and its concomitant downtime. Two hundred tons of fresh -3/4 in. aggregate were used and essentially re-cycled twice for a total throughput in 19 hours of 660 tons. A reserve pile of mixed coarse aggregate (up to 3 inches) was used about once in every size bucket loads in order to maintain the particle size distribution once muck recycling started.

The screen analyses are listed in Appendix B. The particle size distribution remained fairly constant during the 1977 wear tests. The weighted mean particle size ranged from a high of 8.7 mm to a low of 4.1 mm. The moisture contents ranged from 1.0 to 6.6%, more in response to the weather than to artificial watering to alleviate dust.

Following the muck designations outlined in Section 3, the muck used for the 1977 wear tests is classified as muck B and moist.

The last 19 hours of wear testing were comparative in nature, examining different bend liners almost exclusively. For the sake of brevity, only the broad aspects of this test are included here. A more detailed wear report will be issued in 1978 as a Master's thesis by Mr. Ken S. Kostka of the Thayer School of Engineering at Dartmouth College. The basic wear data are on file at the Colorado School of Mines and Dartmouth College.

6.5 LINER MATERIALS TESTED

A. Nihard

Radmark Nihard liners were tested in the 90° flatback bend. A direct comparison of these liners was made with the Radmark D2S alloy liner. Liners of Nihard were placed in the first six locations on the Radmark 90° bend for the first 5 hours of run, after which time they were replaced with D2S alloy liners for the second 5 hours. The Nihard liners were again placed in the first six locations for the final 9 hours of operation.

B. D2S Alloy

The D2S alloy was compared directly to the Nihard liners as stated above. In addition, these liners were placed in the Radmark 30° flatback bend for the first portion of the final 9 hour increment. They were placed in the second, third, and fourth positions of the bend to experience the most severe wear in this bend. This allowed comparison to all the other materials except Nihard tested in the 30° flatback bend.

C. Hard Faced A-36 with/without Rubber Backing

Mild A-36 steel was hard faced with Lincoln Faceweld 12 (see Table 6-2 for material specs) for an evaluation of proposed liner designs. The plates were hard faced with a single pass over the entire surface. First, a comparison was attempted between a hard-faced plate of A-36 steel, and a hard faced A-36 plate with a rubber backing plate supplied by Ardco of Denver. (See Fig. 6-14.) The idea was to see if rubber absorbed some of the kinetic energy of the impacting particles and thereby reducing the impact wear. The hard-faced plate was placed in the system first followed by the rubber backed plate in the 3rd

TABLE 6-2. FACEWELD 12 ANALYSIS

Composition	
C -4.5%	Faceweld 12 is an all-position high
Mn -1.0%	alloy coated tube-type hard-surfacing
Si -1.0%	electrode.
Mo -6.0%	Rockwell C hardness for a single layer
Cr -18.5%	is 45-55.
V - 0.7%	Faceweld 12 is said to be 80-100 times
	more abrasion resistant than 0.3% carbon steel but having one-third its
	impact strength.

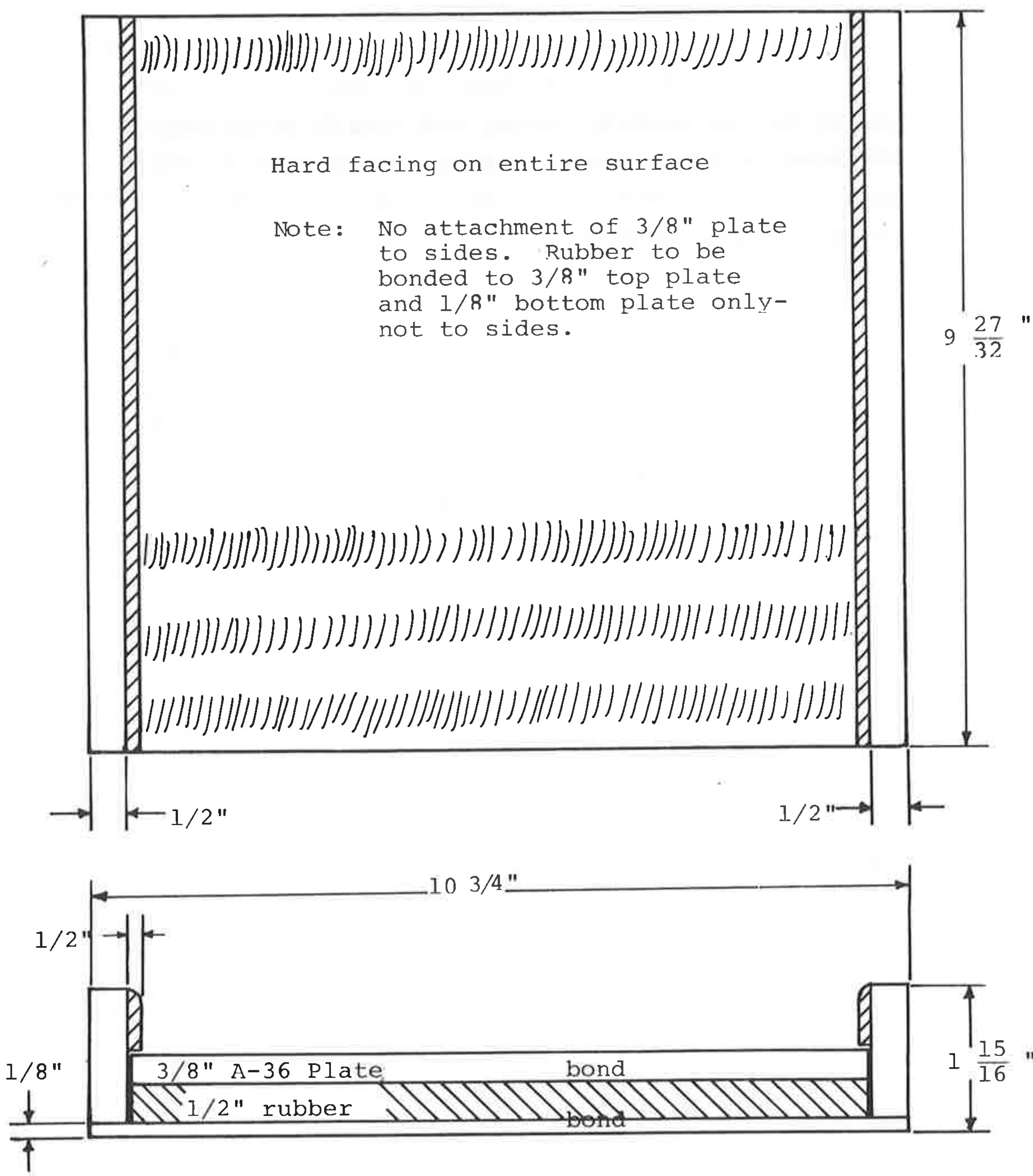


FIG. 6-14. Hard Faced Liner with Rubber Backing

and 4th postitions of the 30^o bend. In addition the hard-faced plates provided an opportunity to check whether hard facings had an acceptable life in the bend. If so, it might prove to be economical for operators of pneumatic pipelines to have their mechanics build up worn areas of liners with hard facing.

D. Cast Iron

Cast iron liners with a high chrome and nickel content (white iron) were cast in the metallurgy lab at the Colorado School of Mines. See Table 6-3 for their composition. The purpose of these liners was to compare performance with these and steel liners subjected to severe impact. Perhaps liners made of cast iron alloy instead of steel would have certain economic advantages. The cast iron liners were placed in the Radmark 30^o and 90^o bends in the last two locations for the entire 1977 test. In addition, liners were placed in the 3rd and 4th locations of the Radmark 30^o bend to subject them to severe wear conditions.

TABLE 6-3. WHITE IRON ANALYSIS

Composition
C - 3.0%
Si -0.5%
Cr -9.8%
Ni -3.1%

E. Rubber

Rubber liners made by Ardco in Denver were tested to determine what role impact plays in wear of the bend liners, assuming that some of the impact energy can be absorbed by a resilient, relatively soft material. Rubber was placed in the 7th, 8th, and 9th positions of the Radmark 90^o bend for the entire test with the exception that the liner in the 7th location was removed to be put in the Radmark 30^{o} bend during the final 2-1/2 hours of testing. Rubber liners were also placed in the 3rd and 4th positions of the Radmark 30^{o} bend for the final 2-1/2 hours. It should be noted from Fig. 6-15 (photo) that the design of the rubber liner is slightly different from that of the other liners. The curved surface (haunch) had two theoretical functions: 1) to add material to the outside portions of the liners (where the liners are clamped into the bends) giving added life to the liner in areas where wear was known to be severe for nonvertical bend configurations, and 2) to raise muck off the bottom of the bend and into the center of the liner for a better distribution of wear on the liner plates, thus giving less wear on the frame of the bend.

6.6 RESULTS

The duration of the wear test was 19 hours with a total throughput of 660 tons. The weight losses for the various bend liners are listed in Table 6-4 for the 30^{o} flatback bend tests and Table 6-5 for the 90^{o} flatback bend tests. The actual weights are listed in Tables C-1 and C-2 in Appendix C. Results of Rockwell hardness testing of the metal liners are listed in Table 6-6. The following statements are of a qualifying nature regarding the tests.

1. Wear was significantly influenced by the location of the liner both with respect to the position within the bend as well as the degree of bend (30^{o} vs 90^{o}).
2. Relatively few samples were tested and, as in all field wear testing, there was a significant variation under assumedly similar test conditions.
3. Unfortunately, it was not possible to test all materials in all bend locations for a comprehensive performance comparison.
4. The hard facing material selected was Faceweld 12 manufactured by Lincoln. As indicated by the composition specification (Table 6-2), it is designed to be more

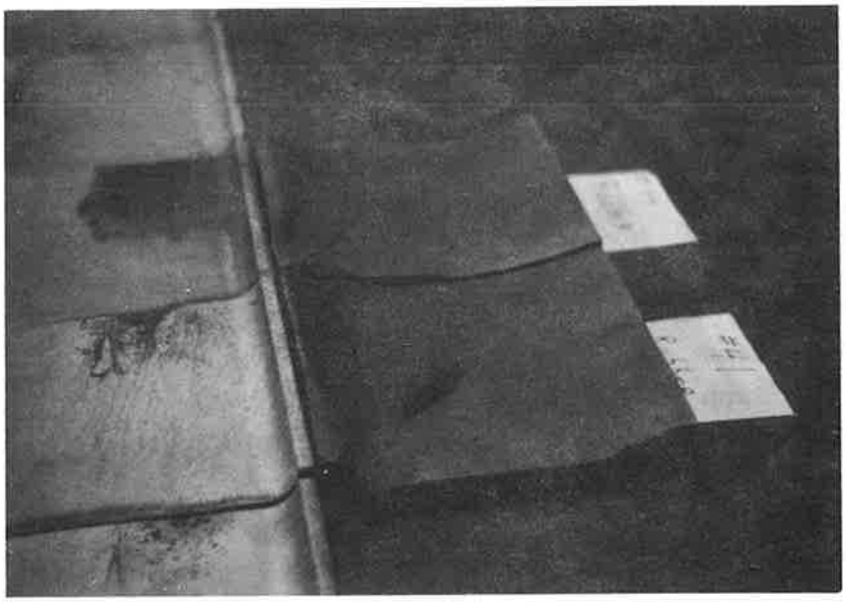


FIG. 6-15. Rubber Liners After 2-1/2 hrs. in 30° Flatback Bend

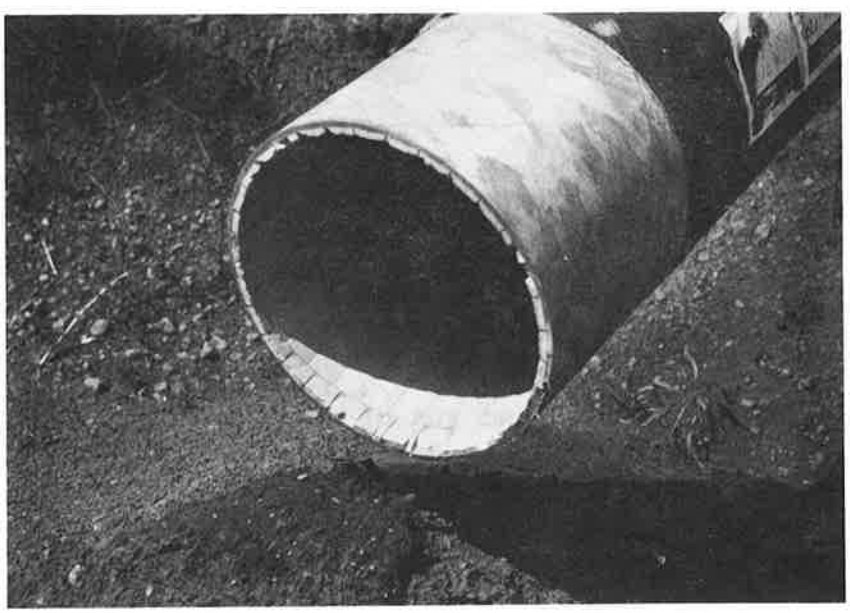


FIG. 6-16. Discharge Pipe (Ceramic Tile-Lined Fiberglass)

TABLE 6-4. WEIGHT LOSS IN KG FOR BEND LINERS-1977 WEAR TEST, 30° FLATBACK BEND

Liner	Material	Location	1st 5 hrs.	2nd 5 hrs.	3rd 5 hrs.	Total
A-10[T]	D2S	#2	0.152	0.133	-	0.285
#61[+]	A-36 w/ hardface	#3	0.727	-	-	0.727
#62[+]	A-36 w/ hardface	#4	0.844	-	-	0.844
#54	Cast Iron	#5	0.753	0.545	0.635	1.933
#55	Cast Iron	#6	0.189	0.142	0.268	0.599
#51[*]	Cast Iron	#3	0.403	-	-	0.403
#56[*]	Cast Iron	#4	1.162	-	-	1.162
#72[†]	A-36 w/ hardface & rubber	#3,4	-	1.239	-	1.239
#71[†]	A-36 w/ hardface & rubber	#4,3	-	1.567	-	1.567
B-16	D2S	#2	-	-	0.216	0.216
B-19[x]	D2S	#3	-	-	0.711	0.711
C-18[x]	D2S	#4	-	-	1.623	1.623
#41[o]	Rubber	#3	-	-	0.321	0.321
#44[o]	Rubber	#4	-	-	0.062	0.062

Notes:

+ These liners were in the system for 2-2/3 hr; liners were switched at 2 hours.

* These liners replaced #61 and #62 after 2-2/3 hr; and were in the system for 2-1/3 hr; #56 was worn through.

† These liners were in for 5 hours but at 2-2/3 hours, they were rotated and switched in position. The liners had worn through in 2-2/3 hours but did not wear through after rotation and run of 2-1/3 hour.

x Replaced in system after $6\frac{37}{60}$ hour by #41 & #44, C-18 had worn through.

o Replaced D2S liners and remained in system $2\frac{37}{60}$ hours. #41 almost worn through, possibly 1 hr. life left before wearing through. Liner #41's weight loss is partly due to $6\frac{37}{60}$ hours in 90° bend.

T A-10 wt. loss only given for 30° bend in this table.

TABLE 6-5. WEIGHT LOSS IN KG FOR BEND LINERS-1977 WEAR TEST, 90° FLATBACK BEND

Liner	Material	Location	1st 5 hrs.	2nd 5 hrs.	3rd 9 hrs.	Total
B-17	Nihard	#1	0.00	-	0.043	0.043
B-15	Nihard	#2	0.170	-	0.237	0.407
C-22	Nihard	#3	0.724	-	0.887	1.611
B-11	Nihard	#4	0.757	-	0.968	1.725
C-17	Nihard	#5	0.622	-	0.850	1.472
B-12	Nihard	#6	0.318	-	0.376	0.694
#41	Rubber	#7	0.080	0.087	-	0.489*
#42	Rubber	#8	0.055	0.029	0.054	0.138
#43	Rubber	#9	0.043	0.030	0.033	0.106
#52	Cast Iron	#10	0.151	0.068	0.139	0.358
#53	Cast Iron	#11	0.119	0.065	0.159	0.343
C-19	D2S	#1	-	0.066	-	0.066
C-20	D2S	#2	-	0.222	-	0.222
C-16	D2S	#3	-	0.316	-	0.316
C-13	D2S	#4	-	0.940	-	0.940
C-21	D2S	#5	-	0.499	-	0.499
C-12	D2S	#6	-	0.663	-	0.663
A-10+	D2S	#7	-	-	-	0.139

* includes wear in 30° Radmark bend

\+ A-10 replaced #41 after $6\frac{37}{60}$ hours and remained in system for $2\frac{37}{60}$ hours to give 0.139

TABLE 6-6. RESULTS OF ROCKWELL HARDNESS TESTING

D2S	Cast Iron	Nihard	Hardfaced Plate #62
1. 59.5	1. 39.0	1. 56.0	1. 36
2. 60.0	2. 41.0	2. 57.0	2. 41
3. 60.0	3. 40.0	3. 57.0	3. 46
4. 60.0	4. 38.0	4. 57.0	4. 5.0*
5. 60.0	5. 41.0	5. 57.0	5. 48
Avg. 59.9	Avg. 39.8	Avg. 56.8	6. 28
			7. 37
			8. 55
			Avg. 41.6 (7rdgs)

*Note: had worn through hardface, bad reading

TABLE 6-7. RELATIVE COMPARISON OF LINERS

Liner Type	Relative Cost	Weight (new) kg	Hardness	Expected Life, Direct Impact
1. Rubber	1	3.4	55 S[1]	3 hours
2. Nihard	1.2	15.5	57 R[2]	6 hours
3. D2S	1.9	15.5	60 R	6 hours
4. Cast Iron	1.1	14.0	40 R	2 hours
5. Hard Faced A-36	2.2	15.5	28 R	2 hours
6. Hardfaced w/Rubber Backing	2.5	10.4	28-55 R	2 hours
7. Polyurethane [3]	.5	3.5 est.	90 S	unknown

Notes:
1. S = Shore A -used for elastomeric substances
2. R = Rockwell -used for metal substances
3. Polyurethane figures are estimates - it was not tested

abrasion resistant than impact resistant. A better material might have been a work hardening manganese rod or a stainless steel rod. The variations in the hard facing as applied (see Table 6-6) appear to have contributed to the early failure of these liners.

5. It is doubtful that the rubber backing acted fully as intended. The hard-faced plate was to float on rubber by bonding the rubber top and bottom but not on the sides. By mistake the rubber was bonded on all sides. Consequently, both hard-faced liners, with and without the rubber backing gave similar wear characteristics. (See Table 6-4.)
6. The cast iron liners lasted about two hours in locations 3 and 4 before wearing through. The hardness was relatively low as noted in Table 6-6.
7. Obviously, wear testing as described here can be interpreted several ways. The emphasis here is on local wear from direct impact at liner locations 3 and 4. Failure is manifested by a liner wearing or "holing" through. The other bend locations are subjected to less wear and would be analyzed by overall wear such as weight loss per unit time or weight loss/unit throughput. It is conceivable that high impact liners should be selected for locations 3 and 4 and high shearing (sliding) wear liners should be selected for the non impact locations. Hence, liner location is paramount in bend wear analyses.

Table 6-7 is a crude relative comparison of the bend liners in terms of cost and wear life where wear life is judged on the basis of holing through from direct impact at bend locations 3 and 4 in the 30° bend. It appears that on this basis, Nihard would rank first with D2S and rubber essentially tied for second place. However, other factors must be considered. The metal liners are five times heavier than rubber and would incur substantial freight costs and handling difficulties compared to rubber. The fact that natural rubber can compete with alloy metals in direct impact applications when handling rocks up to one inch in size is encouraging. The fact that neither liner can withstand a shift period is discouraging.

8. Table 6-8, derived from Tables 6-4 and 6-7, shows percentage weight loss per hour of operation for the various liners tested at different locations in the 30° bend. Since the majority of bend locations are high impact areas 3 and 4, the data are not amenable to ranking the liner materials. The purpose of the table is to show how the liner materials might be evaluated for the non-impact liner locations where overall wear is more important because holing through is much less frequent.
9. The rubber liners as seen in Table 6-7 have a hardness of approximately 55 Shore A. It might be possible to use a harder rubber for this application with better results. It might also be possible to have a hard rubber backed by a softer one, but costs would increase. Also, a waffle construction on the backing of a rubber liner might be an advantage in absorbing impact.

6.7 MISCELLANEOUS WEAR

a) Pipe Wear - no additional measurements were made on pipe wear. Visual inspection did not reveal any excessive wear points. During installation of each pipeline configuration, average care was exercised to maintain straight alignment by eye. No particular joint wear was found upon dismantling the pipeline.

The fiberglass pipe saw 20 hours of service (19 hours with minus 3/4-inch solids, 1 hour with minus 2-inch solids) but showed only small wear depressions downstream of each tile. The wear appeared to be evenly distributed and no tiles were cracked. (See Fig. 6-16 (photo).) The chipped tiles at the end of the pipe were formed when the pipe was cut at the factory.

b) Crusher wear - no substantial wear was observed on the crusher due to its limited use.

c) Radmark Feeder - some wear was observed on the feeder jaws as evidenced by both measurement and increased blowback. The feeder jaws were adjusted inward on two occasions.

TABLE 6-8. PERCENT WEIGHT LOSS KG/HR FOR 30° BEND LINERS - 1977 WEAR TEST

Location	Mat'l	Test Hrs.	Total Wt. Loss	Wt. Loss Per Hour	% of Wt/hr	Notes
#2	D2S	10	0.285	0.028	0.70	
#2	D2S	5	0.216	0.043	0.277	
#3	D2S	6.62	0.711	0.107	0.690	
#3	Cast Iron	2.33	0.403	0.189	1.350	
#3	A36wH.F.	2.67	0.727	0.272	1.755	
#3	Rubber	2.62 in 30° bend 6.62 in 90° bend	0.321	0.036 to 0.129	1.059 to 3.79	
#3&#4	A36wH.F. & Rubber	5	1.239	0.248	2.385	worn through
#3&#4	A36wH.F. & Rubber	5	1.567	0.313	3.010	worn through
#4	D2S	6.62	1.623	0.245	1.581	worn through
#4	A36wH.F.	2.67	0.844	0.316	2.039	
#4	Cast Iron	2.13	1.162	0.546	3.900	worn through
#4	Rubber	2.62	0.062	0.024	0.706	
#5	Cast Iron	15	1.933	0.129	0.921	
#6	Cast Iron	15	0.599	0.040	0.286	

7. EXTENSIBILITY TEST

The transport system at the test installation contained two telescoping sections of pipe which provided the capability of extending the system forward during continuous operation. A description of the pipe sections, ball joints, reducers, supporting skids, etc., was furnished in the earlier report (2).

A chain-driven winch was mounted at the forward end of the muck preparation unit, and was used to pull the system forward during the extension tests. In the proposed tunneling application, the pneumatic transport system is to be pulled forward by the advancing tunnel boring machine, so that a winch would not be required to perform this function.

For the extension tests, a D-8 Caterpillar bulldozer was parked some distance ahead of the transport system and used as an anchor. The winch cable was fitted with a hook which was clipped to the hitch at the rear of the dozer. With the brakes of the dozer locked, the transport system was extended with the winch.

The extension test was performed three times. During each test , the screen, belt and crusher motors of the muck preparation unit were turned on to develop vibrations on the skid surfaces of the sleds. This condition lowered static frictional resistance along the skids during extension of the system, and at the same time reproduced operating conditions under which extension of the system would occur in the proposed application. In addition, all the skids had been greased to reduce both static and kinetic friction.

The first extension was performed while blowing air only. In this test, it was determined that the bulldozer offered sufficient frictional resistance to serve as an anchor, and that extension of the telescopes and skid units was reasonably smooth and unimpeded. Then, the bulldozer turned around and pushed the transport system back to its original position. To prevent buckling of the telescope sleds, 8-in. spikes had been driven into the supporting ties as lateral guides for the sled rails. Hence, during retraction of the system, there was no buckling of the telescope sleds, and the system was returned to its initial configuration without incident.

For the second and third extension tests, muck was put into the system while the system was advanced. Muck loadings ranged from 30 to 110 tph over a period of 1-1/2 hours. The 3/4-inch road base was used initially and then mixed later with minus 1-1/2 inch rock in nearly equal proportions by volume. The telescopes were extended a total of 11 to 12 ft. during the tests, a length corresponding roughly to the dimension of an Esser pipe section. Before extension, the water rings of the telescopes were flushed for a few seconds, but it was found unnecessary to add water to the rings during extension.

The telescopes did not extend at an equal rate during the tests. This was due apparently to a difference in internal frictional resistance from accumulated muck or minor variations in vertical alignment between the two pipe sections. The telescopes were both found to be fully functional. Extension and retraction were both performed smoothly and without difficulty. Retraction was also performed easily with the hydraulic winch mounted at the forward end of the telescope sled.

As a part of evaluating the overall extensibility of the prototype transport system, several sections of Esser pipe were added to the pipeline downstream after the telescopes had been retracted to test the pipe storage rack capability in this aspect of extending the system. The following procedure was employed:

1. The quick-disconnect couplings were removed from the last section of Esser pipe on the telescope sled.
2. The telescopes and the Esser section were winched forward, retracting the unit and leaving an open slot for inserting an additional section of Esser pipe. A winch was installed upstream of the first telescope.

3. The retaining clips in the pipe rack were released, permitting a section of pipe to roll down the pipe rack into position in the line.
4. A "come-along" hand winch was used to close the gap (by extending the telescopes) downstream. A quick-disconnect coupling was installed on the upstream joint of the new section.
5. The "come-along" was again used to winch telescopes and two Esser sections downstream to make the downstream connection with the added pipe section. A quick-disconnect coupling was also fitted to this joint.

The test was repeated. The first test required 23 minutes and the second, 17 minutes. It is estimated that an experienced crew could probably install two new pipe sections within a 10-15 minute interval after each extension.

The pipe replacement tests indicated that several minor problems existed with the pipe rack and quick-disconnect couplings.

1. Some air leakage occurred at pipe joints with the quick-disconnect couplings.
2. When new pipe was added to the line, rotation was often necessary so that the quick-connect couplings could connect without binding on the supporting structure of the pipe rack.
3. An additional winching arrangement was required to pull sections downstream to close the joints and make all connections after new pipe was added.

It may be desirable to modify the design of the quick-connect couplings in order to provide better sealing of temporary joints, and to make the replacement and procedure more efficient. A second hydraulic winch should be installed on the downstream end of the pipe rack to improve pipe handling in the pipe cradle.

8. NOISE LEVEL TEST

Sound level measurements were taken on July 22, 1976, during the capacity tests. On this day the muck used was one part of minus 3-in. rock with two parts of minus 1-1/2 in. aggregate, both in a relatively dry state. The throughput was about 65 tph. Table 8-1 lists the sound levels. The blower and crusher produced the highest noise levels.

TABLE 8-1. SOUND LEVEL MEASUREMENTS

COMPONENT	METER LOCATION	LOADING AIR	LOADING MUCK	dBA
Console	at controls			92
Blower	1m. east	✓		100
Blower	1m. west	✓		101
Feeder	1m. west	✓		91
Crusher	1m. west	✓		95
Crusher	1m. south	✓		83
Crusher	1m. east	✓		94
	3m. east		✓	95
30° bend	1m. east		✓	87
60° bend	1m. east		✓	94
deflector	1m. north	✓		89
	3m. north	✓		86
	1m. north		✓	80
	3m. north		✓	76

Notes: Above readings were taken with the entire system on blowing air alone or blowing muck as designated. In most cases (60°bend and deflector excluded) background noise from the entire system was audible.

The instrument used was a type 2205 Brüel & Kjoer sound level meter, approved by OSHA. It was standardized by sound level calibrator type 4230 at 94 dB prior to the tests. It was used with a wind screen and the background sound, including wind noise, was no greater than 50 dBA and could therefore, be neglected in comparison with the measured levels in the test.

A decibel (dB) is a unit that expresses relative difference in power between acoustic signals. The "A" in dBA signifies a weighting of noise energy that gives less weight to energy at lower frequencies and more nearly approximates the ear's response to sound. The dBA level in an average business office is about 60; heavy street traffic measures about 80 dBA; a jet engine close-up can reach 150 dBA; and a level of 140 dBA is the threshold of pain for most people.

The noise exposure limit set by the 1969 Occupational Safety and Health Act (OSHA) states that the maximum allowable exposure is 6 hours for a noise level of 90 to 92 dBA with hearing conversation set at 85 dBA.

The blower was equipped with one silencer of the reactive type. A reactive silencer consists of several large volume chambers, containing an internal labyrinth arrangement of baffles, compartments, and perforated tubes. This type of silencer smooths out the flow of pulsating type exhausts. Because of the internal arrangement of compartments and tubes, the sound energy is reflected back toward the source thus achieving considerable noise reduction. In general, no acoustic absorption material was used.

It must be emphasized that the noise levels were recorded with the system sitting out in the open with no adjacent structures to reflect the sound waves. In a rock tunnel with the system fully contained, the levels would be quite different. Noise reduction as indicated above was limited to a silencer in the blower discharge. The blower intake with the large volumes of air involved can be a noise generator. The test unit had a large filter-type intake cover that probably reduced the noise somewhat.

9. PNEUMATIC SYSTEM PERFORMANCE

In evaluating the performance of a pipeline system, the concept of specific power has already been discussed. Normally, the power requirement in ft-lb/sec or horsepower is computed from measurements of flowrate, pressure drop, and blower-motor efficiencies. In this case the variables were measured indirectly by electrical input power. For design purposes, a procedure is followed to summate the pressure drops for a pneumatic pipeline system. The procedure for headloss computations is exemplified on the following pages using the pneumatic pipeline characteristics whereever available. The procedure is described in full in Ref. 3 and is not repeated here for the sake of brevity.

Comparison of Measured and Predicted Pressure Drops

Test I-9 (Appendix B) is used as an example. The pertinent data as measured in the field, were:

Test No: I-9, uphill pipeline configuration.
Throughput: 90 stph of E muck (moisture content=5.1 percent).
Ambient Conditions: Temp. 74^{o}F, bar. press.=605.5mm Hg, rel. hum.=60 percent.
Particle Size: WMD=10mm, assume 1/2 in. average size, top size is 30mm. See nomenclature at end of this chapter.
Air Velocity Profiles (Uphill Tests):

Q = 6180 cfm	Rel. hum. = 43 to 68 percent
V = 188.9 ft/s	Temp. = 70-76^{o}F
ρa = 0.9434 g/l	Bar. Press. = 603.5 to 606.3 mm Hg

γa = 0.059 lb/ft^3 where ρa is density and γa is specific weight.

Air Pressure was measured directly downstream of the blower as 10.2 psig and 8.3 psig just upstream of the feeder. Thus, 1.9 psi is lost through the silencer, diverter valve, and 180^{o} elbow. This 2 psi loss was quite consistent throughout the entire test program. Hence, the total pressure drop across the pipeline from the Radmark feeder to the end of the pipeline was equal to less than 8.3 psig due to blowback at the feeder and other losses. The pipeline air pressures are not recorded in Appendix B for the capacity tests but are on file at the Colorado School of Mines.

1. Mass ratio, $M^* = 90$ tph x 2000/(0.059x6180x60) = 8.23
2. Assume solids specific gravity is 2.65

   Density ratio, $\rho^* = \rho_s/\rho_a = 2.65 \times 62.4/0.059 = 2803$
3. Representative particle size = 1/2 in.

   $d/D = 0.05$
4. Pipeline length is 565 ft with one -30°, one -60° bend
5. Acceleration length $L_a = 6D\left[(M_s/\rho a\sqrt{g}.D^{2.5})\sqrt{D}/d.\sqrt{\rho^*}\right]^{1/3}$

$$L_a = 6x\frac{10}{12}\left[\frac{900 \times 2000}{0059\sqrt{32.2}\ 3600} \times 1.2^{2.5}\sqrt{20x2803}\right]^{1/3} = 191 \text{ ft.}$$

6. Acceleration Pressure (occurs in horizontal pipe section)

   From Ref. 3. $A\phi_5(\theta) = 1.0$;

   $V_a^2/gd\rho^{*2} = 189^2/(32.2x1/24x2803^2) = 3.39 \times 10^{-3}$

   Fig. 5-10 gives $A\phi_4(V_a^2/gd\rho^{*2}) = 0.77$ (Ref. 3)

$$P_{acc} = \frac{\rho_a V_a^2}{2}(M^*.A\phi_4(V_a^2/gd\rho^{*2}).A\phi_5(\theta)$$

$$= \frac{0.059}{32.1573} \times \frac{189^2}{2} \times \frac{1}{144}(8.23x0.77x1.0) = 1.442\text{psig}$$

7. Velocity of Solids, V_s

   $A\phi_5(\theta) = 1.0$ for horizontal pipe; 1.05 for 26° slope

   $A\phi_4(V_a^2/gd\rho^{*2}) = 0.77$

   $V_s = V_a(1/2)A\phi_4(V_a^2/gd\rho^{*2})A\phi_5(\theta)$

   $= 189/2 \times 0.77 \times 1.0 = 72.8$fps

   $= 189/2 \times 0.77 \times 1.05 = 76.4$fps for uphill pipe

Note: Since V_a is measured near the end of the pipeline, V_s values are computed for essentially discharge velocities. Smaller particles will travel with higher velocities.

8. Minimum Transport Velocity

$$V_{min} = V_\infty . V_m\phi(d/D) . V_m\phi(\theta) . M_*^{0.3}$$

for $d/D = 0.05$ $\quad V_m\phi(d/D) = 0.7$

for $\theta = 0^o$ (horiz. pipe); $V_m\phi(\theta) = 1.0$ Fig. 5-13, Ref. 3

for $\theta = 26^o$ (uphill); $V_m\phi(\theta) = 1.13$

$$\frac{d}{\left[\frac{3\nu_a^2}{4g(\rho^*-1)}\right]^{1/3}} = \frac{1/24}{\left[\frac{3x1.8^2x10^{-8}}{4x32.2x2802}\right]^{1/3}} = 931$$

From Fig. 5-20 $\quad \frac{V_\infty}{\left[4g\nu(\rho^*-1)/3\right]^{1/3}} = 40$

and $V_\infty = 111$ ft/s

$V_{min} = 111 \times 0.7 \times 1.0 \times 8.23^{0.3} \doteq 146$ ft/s for horiz. pipe

$V_{min} = 165$ fps for uphill pipe. Since minimum transport velocity is greater than velocity of solids, the solids do not flow in complete suspension but roll along the invert of the pipe.

9. Pressure Drop for Established Flow (Eq. 5-15, Ref. 3)

for $M^* = 8.23$; $F\phi_1,(M^*) = 7.0$ from Fig. 5-14
for $d/D = 0.05$; $F\phi_2(d/D) = 1.13$ from Fig. 5-15
for $\varepsilon = 0.75$(est.); $F\phi_3(\varepsilon) = 1.2$ from Fig. 5-16
for $\rho^* = 2803$; $F\phi_4(\rho^*) = 1.0$ from Fig. 5-17
for $\theta = 26^o$; $F\phi_5(\theta) = 1.0$ from Fig. 5-18
for $V_a^2/gD = 189^2/32.2x10/12 = 1331$; $F\phi_6(V_a^2/gD) = 0.0015$

Hence $f_s = 7.0 \times 1.13 \times 1.2 \times 1.0 \times 1.0 \times 0.0015 = 0.01424$

Assume pipewall roughness, k =0.00015 ft.; k/D = 0.00018

Reynolds No. from air velocity profile is 765,000
From Standard Moody-Stanton diagram, $f_a = 0.0147$

$$P_m = (f_a+f_s)V_a^2\rho_a/2(L/D)$$

$$= (0.0147 + 0.01424)\frac{10.059}{32.2} \times \frac{189^2}{2} \times \frac{565}{10} \times \frac{12}{144}$$

= <u>2.265(air)</u> + <u>2.194(solids)</u>, psig

10. Pressure Drop in Bends (Eq. 5-17, Ref. 3)

Add 30^{o} and 60^{o} to make one 90^{o} bend

$A\phi_5(\theta)$ = 1.05 for bends in uphill configuration

$A_4(V_a^{2}/gd\rho^{*2})$ = 0.77 as before

$$\Delta P_b = \frac{0.059}{32.2} \times \frac{189^2}{2} \times 8.23 \times 0.77 \times 1.05 = \underline{1.512 \text{ psig}}$$

Total Pressure Drop (psi/565 ft)

Acceleration Pressure	=	1.442
Airflow	=	2.265
Solids Flow	=	2.194
1 Bend	=	1.512
Total		7.412 psig
Available Pressure	=	8.3 psig

Therefore, 0.9 psig lost in feeder blowback, transitions in telescoping pipes, and deflector.

It can be concluded that this procedure gives reasonable values of pressure drops calculated for dilute-phase pneumatic transport of coarse muck. Unfortunately, the procedure is extensive and complicated. There are eleven graphs accompanying the analysis comprising two functional relationships for the acceleration pressure, two for the minimum transport velocity, and six functional relationships for the solids friction factor. These are explained in Ref. 3.

Nomenclature

f_a = Darcy-Weisbach friction factor for airflow

f_s = Darcy-Weisbach friction factor for solids phase

$F\phi$ = function relating friction factor to parameters M*, d/D, etc.

ΔP_{sb} = pressure drop in lb/ft^2 for reaccelerating solids around bends

L_a = Length of pipe in feet required to accelerate solids from zero velocity at the feeder to terminal velocity.

D = inside diameter of pipe in feet

M_s = mass flow rate of solids, lb/sec

γ_f = specific weight of air (0.075 lb/ft^3 at sea level, 0.06 lb/ft^3 at CSM test site)

g = gravitational acceleration, 32.2 ft/sec^2

d = representative particle size, feet (A weighted mean particle size can be used.)

ρ^* = density of solids, $\rho_s (lb_m/ft^3)$, density of air $\rho_a (lb_m/ft^3)$

ΔP_{acc} = pressure in lb/ft^2 required to accelerate solids to terminal velocity

V_a = mean velocity of airstream, ft/sec

M^* = mass flow rate of solids, M_s(lb/sec) mass flow rate of air, M_a(lb/sec)

$A\phi_4$ = acceleration function relating pressure drop to densimetric Froude No. $V_a^2/gd\rho^*$ (Note: all functions are dimensionless.)

$A\phi_5$ = acceleration function relating pressure drop to pipe inclination measured upward from horizontal

V_s = mean velocity of solids, ft/sec

V_{min} = minimum transport velocity, ft/sec

V_∞ = terminal settling velocity of mean representative particle in an infinite fluid, ft/sec

$V_m\phi$ = function relating minimum transport velocity with representative particle size to pipe diameter ratio (d/D) or to pipe inclination Θ, measured upward from horizontal

ΔP_m = total pressure of solids-gaseous mixture required for established flow, lb/ft^2

L = length of pipeline over which pressure drop is measured, ft .

10. SYSTEM OPERATIONAL CHARACTERISTICS

A prototype pneumatic pipeline system such as the one studied here has many facets with respect to operation. This chapter comments on miscellaneous aspects and their operational characteristics.

10.1 MAINTENANCE REQUIREMENTS

Maintenance was divided into four component areas: crusher, feeder, blower, and pipeline. Maintenance scheduling was on an annual, monthly, and daily basis. The equipment was winterized twice, which involved covering the various belt drives, motors, blower, and console against the elements.

The lubrication schedule supplied by Radmark was adhered to. The major problem with lubrication was on the blower drive which experienced lube leakage at the bearings. This was a design fault which could be easily rectified by the manufacturer. Another inconvenient lube problem occurred late in the test program when ground squirrels ate the outer covering of a hydraulic hose thus requiring replacement of hose and 40 gallons of oil for the hydraulic system driving the Radmark feeder.

The muck preparation unit was fabricated locally from available and inexpensive used parts. The throughput was limited in the test program and did not justify a fully refined design with optimum components. Consequently, the unit required more maintenance than the other components. The common problems were loosening of bolts due to vibrations from the vibrating screen, V-belts slipping off pulleys, large rocks jamming belts, and belts going out of alignment. One conveyor belt motor burned out during a rock jam and had to be replaced. A commercially designed muck preparation unit would not be likely to experience these problems to the same degree. Maintenance of the muck preparation unit was on a daily basis for most of the test program and on an hourly basis for high muck loadings or coarse muck loadings.

Blower maintenance was limited to daily checks on bearing lube and rarely on slippage or overturning of the V-belts on the blower-motor drive system. The drive system was a used item.

Feeder maintenance on both Radmark and Syntron components was more frequent, calling for removal of caked slimes when wet fines were transported and periodic cleaning of the Radmark feeder from excessive blowback. The clean-out in the tee-section of pipe below the feeder never had to be opened to unclog a jammed pipe. The movable jaws were adjusted twice in the study. The Syntron pan feeder required minor maintenance by a local service man on two occasions; once for resetting the airgap between the armature and core, another time for replacing a burned-out coil in the electrical panel. One noticeable feature of the pan feeder was that it operated best in a horizontal plane. When the pipeline system was extended, the train of equipment moved downhill and the pan feeder had to be rebalanced. In a tunnel application, some provision would have to be made for such a feeder to be easily adjusted to a horizontal position.

A few pressure gauges had to be replaced occasionally but on a routine basis.

Maintenance on the pipeline was minimal except when elbow liners were replaced. Excessive leaks through pipeline connections or worn elbows or transition sections (10"x8" reducers) were obvious by their hissing noise and a noted reduction in operating pressure.

10.2 RELIABILITY

Reliability or availability of the system during the limited tests was good. Reliability was proportional to the amount of maintenance required on each component. The reliability, in decreasing order was: pipeline, blower, feeder, and muck preparation unit. However, when numerous elbows were in the pipeline, as during the wear tests, the elbows became the least reliable component.

During the test program, it was more often a case of manpower and front-end loader unavailability rather than the system which caused delays in testing.

10.3 EXTENSIBILITY

Extensibility as discussed in Section 7 posed no problems. Two telescopes worked well in series suggesting that possibly three or four could be used in series. The transition pipe between telescopes consisted of a 10"x8" reducer. These should be lengthened and hardened to resist wear. Only minor water lubrication of the telescopes prior to extensibility was necessary. However, it is possible that fine muck would require water lubrication during extensibility. Air leakage from the telescopes was not evident.

10.4 AIR LEAKS AND FEEDER BLOWBACK

The flatback elbows were the source of most of the air leaks in the pipeline. The flat covers of the elbows would bow under bolt tension and allow air to escape. If the leaks were small, they were often self-sealing from the fines in the muck. During most of the tests, however, the leaks were relatively large and there were insufficient fines so the system had to be shut down while thicker gaskets were installed in the elbows. Leaks were considered unacceptable when the free running pressure (no muck load condition) decreased by 1/2 psig.

Feeder blowback produced the most noticeable leak in the system. Blowback develops when a rotary airlock or star feeder such as the Radmark, rotating at 35 rpm with eight pockets, cannot be sealed perfectly from the atmosphere. Under a pipeline pressure of 10 to 15 psig, there is always some rotor leakage which, if excessive, blows fines into the area above the feeder. This can be reduced but not eliminated by shrouding the feeder entry chute and ensuring that the rotor has worn evenly and is always in good adjustment

(0.010 in.) with the stator (side jaws). Figs. 10-1 and 10-2 (photos) show the wooden shrouding C-clamped into position on the entry chute of the Radmark feeder. Fig. 10-3 (photo) shows an accumulation of fines around the feeder from stationary (not advancing) operation.

10.5 OPERATION

The system was remarkably easy to operate with no particular skills required. The crew size was small consisting of a console operator, a "greaser", and a recorder. Depending on the type of test, as few as two men were used, or as many as four men. These totals do not include the front-end loader operator who in essence substituted for the tunnel boring machine operator.

The console operator was responsible for the desired muck throughput in the system by controlling the rate of muck fed from the Syntron pan feeder. The "greaser" inspected the system looking for potential trouble spots or making necessary small adjustments. He walked the pipeline to detect leaks due to wear or elbow cover leaks. The recorder documented data as it was generated.

10.6 SAFETY

No accidents occurred on the project. There appeared to be no potential hazards of a catastrophic nature during operation. As mentioned elsewhere, there were pressure cut-offs consisting of the following:

Syntron pan feeder: 12 psig max.

Radmark feeder hydraulic pressure: 1800 psig max.

Blower: 15 psig max.

Probably the most dangerous areas around the system were the crusher, which ejected large rocks down a chute off the 8-inch grizzly above the vibrating screen, and the discharge end of the pipeline, where stones were projected at high velocities. In the inclined pipeline configuration, the deflector was fenced to keep grazing horses away.

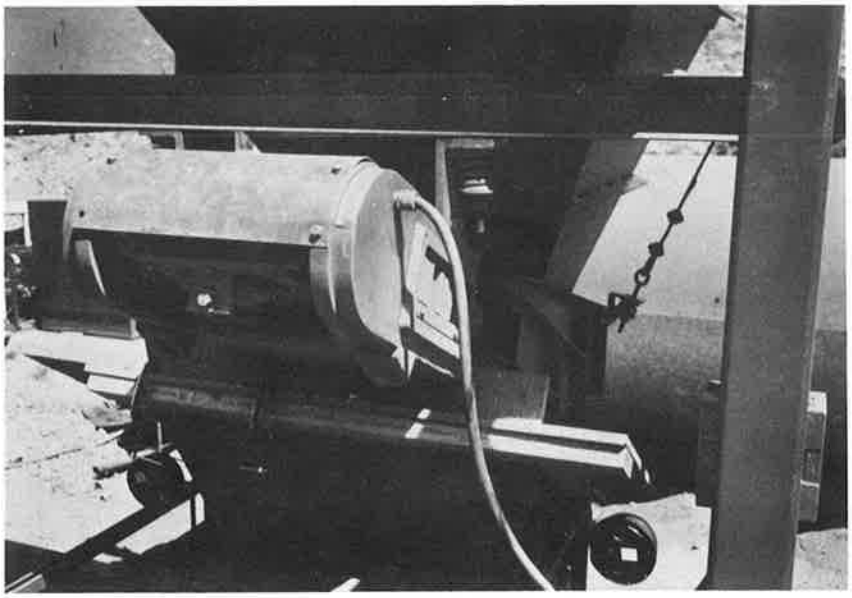


FIG. 10-1. Front View of Wooden Shrouding on Feeder

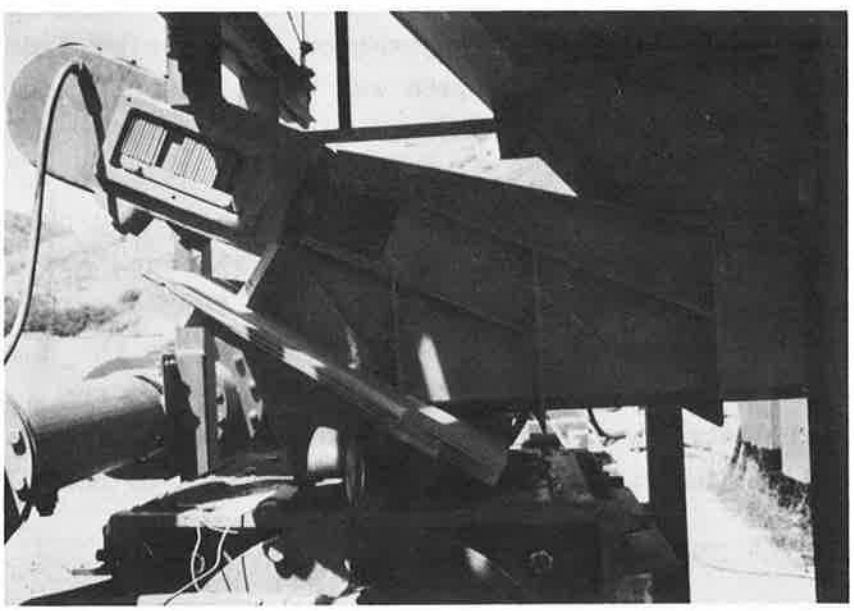


FIG. 10-2. Side View of Wooden Shrouding on Feeder

FIG. 10-3. Fines Around Feeder from Blowback

10.7 DUST CONTROL

Dust was a problem only on a few occasions; at the first start-ups after pipeline installation on the hill and in the horizontal configuration, and during a dry spell when minus 1/2 inch aggregate was used. The former cases were short-lived; the latter case was readily corrected by use of the water ring.

Water was available during the horizontal pipeline wear tests. It was stored in a 2000-gal. tank and was pumped through hoses to a standby hose for watering the muck piles prior to their being dumped into the muck preparation unit. Another hose was connected to the water ring mounted upstream of the pipeline discharge. Flow was metered and it was found that 1 or 2 gpm was ample to control dust.

10.8 SPOIL PILE CHARACTERISTICS

The spoil pile created during the capacity tests was not reclaimed. It was clean and contained many large angular rocks as shown in Fig. 5-5 of Section 5. Fig. 10-4 (photo) shows a close-up of the spoil in the hillside slot during the wear tests. This muck had been recirculated several times. Note the rounded aggregate and presence of fines.

The length of the rock trajectories, their speed and rebound characteristics off the spoil pile were quite impressive. Trajectories were in excess of 100 ft. for rock larger than 1 inch.

10.9 PIPELINE

The Esser pipe, because of its weight, was installed in double lengths (22 ft.) using slings and a bulldozer. The male-female connections with O-rings ensured good alignment but required more time to connect. "Eye-ball precision" was used to set the alignment. The Esser pipe was never rotated during the test program. The pipe had "raised dots" located every 120° on its outer circumference to assist in rotation for prolonged service if required.

FIG. 10-4. Recycled Muck and Generation of Fines

All the pipe was installed in both inclined and horizontal configuration with a single "dot" showing in the 12 o'clock position.

10.10 WEATHER

The tests were performed in every month of the year except from January through March. Temperatures ranged from 35 to 100°F and the weather varied from rain and fog to high heat and low humidity. The system never exhibited obvious weather-dependent characteristics other than the fact that the pipeline air temperature measured just downstream of the blower was a function of ambient air temperature and pressure. Each increment of pressure raised the pipeline air temperature by about 12°F at the test site. For example, if the air temperature was 40°F and the blower developed 10 psig, the pipeline air temperature was about 160°F (6000 ft. above sea level).

Numerous other variables such as moisture content, particle size and distribution, and muck-throughput easily masked the effect of air temperature on performance characteristics.

11. CONCLUSIONS

11.1 CAPACITY

With a minimum number of elbows, the pneumatic pipeline system as tested was capable of transporting coarse muck at rates in excess of 100 stph. Larger throughputs could have been transported at lower altitudes if smaller safety factors were applied to overload protection devices on the equipment. There appear to be no technical constraints to building larger equipment to transport higher throughputs.

11.2 POWER REQUIREMENTS

The optimum power requirements occurred between 60 and 100 stph for the mucks used in this system. The blower specific power (90 percent of total system power) ranged from 4.5 to 9.4 kw-hr/short ton-1000 ft. (including a 160 ft. lift) depending on muck characteristics. This represents more than a two-fold range in power consumption but is indicative of the wide range of muck characteristics. By contrast, a slurry pipeline system can deliver minus 1-inch aggregate (WMD=11.6mm)* at the rate of 100 stph in a horizontal pipe for a specific power of 0.45 kw-hr, roughly 1/10th the power (3). These are transportation requirements only and do not include muck Preparation for either pipeline mode or dewatering for the slurry pipeline modes.

11.3 WEAR

Wear is extensive on elbows, particularly flatback elbows in horizontal configurations. Round elbows have better wear life in horizontal configurations. However, judging by the results obtained in this study, wear life for any elbow geometry in pneumatic pipelines transporting coarse muck is <u>not impressive</u>.

*WMD = Weignted mean diameter particle size.

11.4 EFFECT OF MOISTURE

For the range of muck size studied (1/2 in. to 3 in.), moisture content is more important than particle size on the power requirements for pipeline transportation. There is a critical level of moisture below which the solids are lubricated and flow easily into the feeder and above which cohesive effects predominate causing the muck to be sticky. Power requirements for pipeline transportation of solids are reduced by higher moisture contents in larger particle sizes and increased by higher moisture contents in smaller particle sizes. Speculation suggests a possible explanation: a) moisture in large particles (which have small specific surface areas) is readily evaporated by the warm pipeline air giving a greater air density and viscosity which can support larger particles in suspension thereby reducing particle-wall friction; b) moisture in small particles (which have high specific surface areas) exerts high surface tension forces to hold finer particles together resulting in higher pressure drops to transport these agglomerates.

11.5 EXTENSIBILITY

Advancement of the muck haulage system can be achieved by telescoping pipes. Twenty-two feet of telescoping was performed successfully, leading to the conclusion that probably 50 feet could be attained without much difficulty.

11.6 NOISE

The pneumatic pipeline system is noisy at the muck preparation unit and blower but not inordinately for this kind of operation. Noise levels can be reduced by use of multiple silencers and other design refinements.

11.7 SAFETY

A pneumatic pipeline system is a safe muck haulage system. It is a low pressure system, requires few operators, and utilizes simple, rugged equipment.

11.8 RECOMMENDATIONS

1. It appears that little can be done about the power intensity of a pneumatic pipeline system transporting coarse muck.
2. Elbow wear is the area requiring the most immediate further work to provide acceptable system operational life.
   a) Tests are recommended to establish the relative wear severity in 90^{o} bends with a varying radius of curvature. These tests would ascertain the optimum incident impingement angle at the primary impact point for a given material.
   b) The following materials or combinations of materials should be tested for use in the pneumatic system:
      1) Polyurethane, with a hardness of 90 Shore A and characteristics like those of rubber.
      2) Hard facing with (1) manganese and (2) stainless steel
      3) Rubber with hardness greater than 55 Shore A
      4) Rubber liners with hard materials like tungsten carbide and ceramic tiles molded into the surface exposed to wear.
   c) Assuming that all elbows will experience wear on the outside curve which redirects the flow, other design configurations should be investigated to improve the ease and speed with which replacement liners can be installed.
   d) Attempts to bring the wear problem under control for both the straight pipe and the elbows has lead to units that are very heavy to move, rotate and install. Consideration should be given to fiberglass, rubber, or plastic casings.
   e) Study should be directed toward wear identification by remote means so that maintenance can be scheduled. Ultrasonics may be useful for this application.

11.9 APPLICATIONS

The following comments pertain to a pneumatic pipeline system transporting coarse abrasive solids.

A pneumatic pipeline is a power-intensive muck haulage system. It is sensitive to the moisture content of the muck more so than to particle size when transporting muck larger than 1/2 inch in size.

A pneumatic transport system is limited by the severe wear that can occur whenever the direction of flow is changed. Wear in straight sections with reasonable alignment can be kept to economical levels with special pipe. Pipe rotation extends pipeline life by distributing the wear that tends to concentrate at the bottom around the circumference. Vertical pipe wear is significantly less because the bottom wear is eliminated.

A pneumatic pipeline has a low captial cost, requires few operators, is simple to operate, and appears relatively safe.

The pneumatic system has fast start-up and shut-down capabilities because of short elapsed time to clear the pipeline. Since no fluids are involved, there are no problems with freezing and corrosion.

Since air is the conveying vehicle, there is no problem with availability or disposal as there is with slurry systems.

Pneumatic pipeline noise levels at the input end can be substantial. This should be recognized in any installation with special consideration being given to isolation of the noise generators.

While the blower-feeder units in a pneumatic system are relatively massive, the overall configuration is compact and has a low silhouette.

Air volumes required for high tonnage transport are substantial. In designing a tunnel ventilation system, consideration might be given to an external location for the blower.

Piping the air to the feeder would then require a double pipe system.

The optimum pipeline system would be one without elbows. In tunneling this would represent a pipeline discharging straight out of a tunnel through a portal.

In hoisting, ideally the pneumatic system would raise muck vertically with one elbow at the bottom of the shaft and another at the surface to direct the muck into a collection hopper. The surface elbow would be one size larger than the pipeline and would be accessible for maintenance. The numerous installations of pneumatic hoisting systems in deep underground coal mines in the United Kingdom attest to the potential and safety of this application.

Some concern has been raised about the possibility of explosions when coal is transported in underground mines. While beyond the scope of this study the reader is referred to recent work by the U.S. Bureau of Mines(10) which suggests that mixtures of coal dust and methane are explosive mixtures but are unlikely to be ignited by tramp rock or metal flowing in a pipeline.

Stowing backfill in an under-ground mine probably represents the most difficult application of a pneumatic pipeline system because of the numerous elbows generally required. However, where water is neither desirable nor available, a pneumatic pipeline system may be the only option.

Pneumatic pipelines transporting coarse heavy muck are by nature, low-capacity, short-distance haulage systems when compared to conventional muck haulage systems for tunnel excavation(11). Horizontal transport of coarse rock is probably limited by currently available equipment to distances up to 2000 ft. and capacities up to 200 tph. Vertical transport is probably limited to 1500 ft. and 100 tph.

A pneumatic pipeline can provide an extensible link between an advancing tunneling machine and a semi-permanent or permanent transport system.

12. REFERENCES

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APPENDIX A

AIRSTREAM VELOCITY PROFILES

Table A-1 lists the Pitot-static tube positions and water gage readings taken during the uphill and horizontal pipeline configurations. The calculated velocities in feet per sec are also shown. These were obtained from the Pitot-static tube equation

$$U_r = C_p \sqrt{2g \frac{\Delta}{12} \left(\frac{\gamma w}{\gamma a} -1 \right)} \qquad \text{(A-1)}$$

where U_r = local velocity, ft/sec, measured at some radius r from center-line of pipe.

C_p = Pitot-static tube coefficient, assumed equal to 0.99.

g = gravitational acceleration, 32.1573 ft/sec^2.

Δ = manometer deflection in inches of water.

γw = specific weight of water at ambient temperature conditions.

γa = specific weight of air at ambient conditions of temperature, pressure, and humidity.

The specific weights (densities) of water and air were obtained from the "Handbook of Chemistry and Physics, 52nd Edition (1971-72) by the Chemical Rubber Co. The equation for the density of moist air is given by

$$pa = 1.2929(273.13/T) \left[(B-0.3783e)/760\right] \qquad \text{(A-2)}$$

where pa = density of moist air, g/ℓ

T = absolute temperature, ^{o}K

B = barometric pressure, mm Hg

e = vapor pressure of moisture in air, mm

TABLE A-1. PITOT TUBE DIFFERENTIAL PRESSURES/VELOCITIES (inches water gage/ft/s) I.D.=10.020 in.

Date	13 July 76	14 July 76	15 July 76	16 July 76	26 July 76
Pipeline	inclined	inclined	inclined	inclined	inclined
Top(0.125")	5.65/176.9	5.10/169.5	5.25/168.9	5.10/170.1	5.40/173.3
0.76	6.10/183.8	5.85/181.6	6.10/182.1	5.95/183.7	6.10/184.2
0.82	6.35/187.5	5.95/183.1	6.15/182.8	5.98/184.2	6.18/185.4
1.47	6.80/194.1	6.50/191.4	6.75/191.5	6.53/192.4	6.70/193.0
2.08	7.85/208.5	6.95/197.9	7.27/198.8	7.02/199.5	7.14/199.3
3.43	8.05/211.1	7.55/206.3	7.83/206.3	7.50/206.2	7.55/204.9
C_L 5.00	7.75/207.2	7.25/202.1	7.66/204.0	7.28/203.2	7.36/202.3
6.59	7.15/199.0	6.48/191.1	6.80/192.2	6.42/190.8	6.90/195.9
7.94	5.95/181.5	5.60/177.6	5.68/175.7	5.52/176.9	6.06/183.6
8.56	5.05/167.2	4.40/157.5	4.69/159.6	4.73/163.8	5.68/177.7
9.20	4.05/149.8	3.65/143.4	4.55/157.2	4.25/155.3	4.92/165.4
9.26	4.30/154.3	3.50/140.4	4.30/152.9	4.15/153.4	4.78/163.0
Bot. 9.90	-	3.45/139.4	4.85/162.3	3.60/142.9	3.46/138.7
Bar. Press. mm Hg	603.5	604.0	608.1	608.1	606.3
Pipe Air, T°F	138	148	142	148	147
Amb. Air, T°C	21.1	27.2	18.3	31.7	24.4
Rel. Hum. %	68	42	69	24	43
ρa, g/ℓ	0.9457	0.9281	0.9642	0.9207	0.9411
ρw, g/cc	0.9980	0.9965	0.9985	0.9950	0.9973
μa, cp	0.018	-	-	-	0.018
Re	770,886	-	-	-	762,386

TABLE A-1. PITOT TUBE DIFFERENTIAL PRESSURES/VELOCITIES(Cont'd)
(inches water gage/ft/s) I.D. = 10.020 in.

Date	17 Aug 76	19 Aug 76	15 Nov 76	18 Nov 76
Pipeline	horizontal	horizontal	horizontal	horizontal
Top(0.125)	4.75/163.4	5.05/166.4	4.92/159.3	5.30/169.4
0.26	5.10/169.4	5.35/171.2	5.22/164.0	5.65/174.9
0.82	5.67/178.6	5.87/179.4	5.78/172.6	6.20/183.2
1.47	6.13/185.7	6.32/186.1	6.23/179.2	6.48/187.3
2.08	6.40/189.7	6.19/184.2	6.50/183.1	6.56/188.5
3.43	6.60/192.7	6.91/194.6	6.72/186.1	6.45/186.9
℄ 5.00	6.32/188.5	6.75/192.4	6.50/183.1	6.33/185.1
6.59	6.08/184.9	6.58/189.9	6.45/182.3	6.30/184.7
7.94	5.45/175.1	5.83/178.8	5.75/172.2	6.15/182.5
8.56	5.05/168.5	5.24/169.5	5.32/165.6	5.65/174.9
9.20	4.35/156.4	4.58/158.4	4.55/153.2	4.75/160.4
9.26	3.19/133.9	3.31/134.7	3.30/130.4	3.35/134.7
Bot.9.90	2.95/128.8	3.15/131.4	3.10/126.4	3.18/131.2
Bar.Press. mm Hg	604.5	606.4	604.0	602.1
Pipe Air, T^oF	-	120	-	-
Amb.Air, T^oC	27.5	20.0	2.2	14.5
Rel.Hum.%	29	50	72	48
ρa,g/	0.9298	0.9557	1.0178	0.9685
ρw,g/cc	0.9964	0.9982	0.9999	0.9992
μ_a,cp	0.0182	-	-	0.0175
Re	707,982	-	-	771,233

The Reynolds number for airflow in a 10-inch diameter pipe was calculated from:

$$Re = VD\rho a/\mu_a \qquad \text{(A-3)}$$

where Re = Reynolds number

V = mean velocity of flow, ft/sec

D = inside pipe diameter, feet

ρa = density of air, g/cc

μ_a = dynamic viscosity of air, poise.

APPENDIX B

CAPACITY TEST RESULTS

AND SCREEN ANALYSES

TABLE B-1.
Capacity Test Data

DATE July 15, 1976

TEST I-1

DURATION OF TEST 0.82 hr.

INPUT MATERIAL

Pipeline Muck: A moist
No. of Screen Analyses: 2
Average Moisture(%): 2.4

GENERAL CONDITIONS

Avg. Air Temp.(°F): 65
Avg. Barometric Pres(mmHg): 607.8
Avg. Relative Humidity%: 67

VARIABLE	SYNTRON SETTING (%)					
	15	30	40	30		
Muck Throughput (stph)	24	53	74	53		
Crusher (hp)	21.6	21.1	22.1	20.0		
Feeder (hp)	11.0	11.1	13.1	9.3		
Blower (hp)	217.2	267.1	353.0	256.9		
Total Power (hp)	249.8	299.3	388.2	286.2		
Power Factor (%)	63	70	78	59		
Pipe Air Temp (°F)	143	162	206	172		
Line Air Pressure (psig)	5.7	7.4	10.5	7.0		
Kw-hr/S.Ton-1000 ft.*	11.9	6.65	6.29	6.40		

$$* \text{ Specific Transport Power} = \frac{\text{blower hp for 565 ft.}}{1.341 \text{ hp/kw}} \times \frac{1000\text{ft.}}{565\text{ft.}} \times \frac{1}{\text{short tons/hr}}$$

TEST I-1 7/15/76 (MINUS .5" MOIST)
MINUS .75" MUCK: .5" VIBE SCREEN
SAMPLE #1

MESH	PERCENT	SUM %
0.500/ 0.371	5.00	5.0
0.371/ 4	18.10	23.1
4/ 8	21.80	44.9
8/ 16	18.10	63.0
16/ 30	17.80	80.8
30/ 50	6.70	87.5
50/100	6.80	94.3
100/PAN	5.70	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =3.0940E+00 MM
COEFF. OF VARIATION = 96.83266
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 2.854239) ** 0.913460)
SLOPE = 0.913460 INTERCEPT B = 2.85423851000 MILLIMETERS
CORRELATION COEFF. = 0.996887 D50 = 1.98 MILLIMETERS

TEST I-1 7/15/76 (MINUS .5" MOIST)
MINUS .75" MUCK: .5" VIBE SCREEN
SAMPLE #2

MESH	PERCENT	SUM %
0.650/ 0.525	7.10	7.1
0.525/ 0.371	17.30	24.4
0.371/ 4	19.20	43.6
4/ 8	13.70	57.3
8/ 28	17.40	74.7
28/ 65	13.40	88.1
65/100	4.30	92.4
100/PAN	7.60	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =5.1964E+00 MM
COEFF. OF VARIATION = 92.18099
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 4.737623) ** 0.691369)
SLOPE = 0.691369 INTERCEPT B = 4.73762298000 MILLIMETERS
CORRELATION COEFF. = 0.989583 D50 = 3.62 MILLIMETERS

TABLE B-2.
Capacity Test Data

DATE July 15, 1976

TEST I-2

DURATION OF TEST 0.54 hr.

INPUT MATERIAL

Pipeline Muck: A wet
No. of Screen Analyses: 2
Average Moisture(%): 4%

GENERAL CONDITIONS

Avg. Air Temp.(°F): 68
Avg. Barometric Pres(mmHg): 607.9
Avg. Relative Humidity %: 62

VARIABLE / **SYNTRON SETTING(%)**

	15	30	45			
Muck Throughput(stph)	14.7	39	64			
Crusher (hp)	17.4	17.8	20.2			
Feeder (hp)	9.3	9.3	9.5			
Blower (hp)	189.9	222.6	305.7			
Total Power(hp)	216.6	249.7	335.5			
Power Factor(%)	60	67	77			
Pipe Air Temp(°F)	141	155	192			
Line Air Pressure(psig)	4.7	5.7	9.4			
Kw-hr/S.Ton-1000 ft.	17.1	7.57	6.30			

TEST I-2 7/15/76 (MINUS .5" WET)
MINUS .75" MUCK: .5" VIBE SCREEN
SAMPLE #1

MESH	PERCENT	SUM %
0.500/ 0.371	14.30	14.3
0.371/ 4	22.10	36.4
4/ 8	18.50	54.9
8/ 16	12.30	67.2
16/ 30	13.00	80.2
30/ 50	11.00	91.2
50/100	6.70	97.9
100/PAN	2.10	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =4.1693E+00 MM
COEFF. OF VARIATION = 89.57078
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 3.910689) ** 0.980745)
SLOPE = 0.980745 INTERCEPT B = 3.91068870000 MILLIMETERS
CORRELATION COEFF. = 0.968529 D50 = 2.99 MILLIMETERS

TEST I-2 7/15/76 (MINUS .5" WET)
MINUS .75" MUCK: .5" VIBE SCREEN
SAMPLE #2

MESH	PERCENT	SUM %
0.500/ 4	21.20	21.2
4/ 8	21.20	42.4
8/ 16	15.30	57.7
16/ 30	11.30	69.0
30/ 70	15.70	84.7
70/100	4.80	89.5
100/140	5.00	94.5
140/PAN	5.50	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =3.0197E+00 MM
REGIME = TURBULENT
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 2.432023) ** 0.807301)
SLOPE = 0.807301 INTERCEPT B = 2.43202254000 MILLIMETERS
CORRELATION COEFF. = 0.984371 D50 = 1.68 MILLIMETERS

TABLE B-3.
Capacity Test Data

DATE July14, 1976

TEST I-3

DURATION OF TEST 1.80 hr.

INPUT MATERIAL

Pipeline Muck: B very wet
No. of Screen Analyses: 3
Average Moisture(%): 7.0

GENERAL CONDITIONS

Avg. Air Temp.(°F): 85
Avg. Barometric Pres(mmHg): 604.5
Avg. Relative Humidity%: 29

VARIABLE — **SYNTRON SETTING(%)**

	10	20	30	45	20	
Muck Throughput(stph)	9.8	25	42	73	25	
Crusher (hp)	16.6	14.6	16.1	16.2	15.8	
Feeder (hp)	9.5	9.1	9.5	10.3	9.3	
Blower (hp)	213.0	231.2	254.3	332.6	200.1	
Total Power(hp)	239.1	255.2	279.9	359.1	225.2	
Power Factor(%)	67	69	71	77	62	
Pipe Air Temp(°F)	164	183	192	209	177	
Line Air Pressure(psig)	5.6	6.5	7.1	10.2	5.0	
Kw-hr/S.Ton-1000 ft.	28.7	12.4	7.99	6.05	10.7	

TEST I-2 7/15/76 (MINUS .5" WET)
MINUS .75" MUCK: .5" VIBE SCREEN
SAMPLE #3

MESH	PERCENT	SUM %
0.500/ 0.371	6.40	6.4
0.371/ 4	18.30	24.7
4/ 8	11.00	35.7
8/ 16	25.20	60.9
16/ 30	15.00	75.9
30/ 50	11.20	87.1
50/100	7.70	94.8
100/PAN	5.20	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =2.9980E+00 MM
COEFF. OF VARIATION = 106.56776
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 2.708652) ** 0.904990)
SLOPE = 0.904990 INTERCEPT B = 2.70865238000 MILLIMETERS
CORRELATION COEFF. = 0.990059 D50 = 1.59 MILLIMETERS

TEST I-3 7/14/76 (MINUS .75" WET)
MINUS .75" MUCK: 1" VIBE SCREEN
SAMPLE #1

MESH	PERCENT	SUM %
0.750/ 0.371	8.50	8.5
0.371/ 4	11.90	20.4
4/ 18	22.20	42.6
18/ 50	27.20	69.8
50/ 70	6.00	75.8
70/140	11.00	86.8
140/200	8.90	95.7
200/PAN	4.30	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =2.8830E+00 MM
COEFF. OF VARIATION = 141.91768
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 1.949415) ** 0.718146)
SLOPE = 0.718146 INTERCEPT B = 1.94941476000 MILLIMETERS
CORRELATION COEFF. = 0.954090 D50 = 0.74 MILLIMETERS

TEST I-3 7/14/76 (MINUS .75" WET)
MINUS .75" MUCK: 1" VIBE SCREEN
SAMPLE #2

MESH	PERCENT	SUM %
0.750/ 0.371	22.40	22.4
0.371/ 4	17.50	39.9
4/ 18	18.50	58.4
18/ 35	11.50	69.9
35/ 50	7.20	77.1
50/ 70	10.50	87.6
70/100	9.20	96.8
100/PAN	3.20	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =5.0951E+00 MM
COEFF. OF VARIATION = 107.02691
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 3.901859) ** 0.711176)
SLOPE = 0.711176 INTERCEPT B = 3.90185869000 MILLIMETERS
CORRELATION COEFF. = 0.889453 D50 = 2.64 MILLIMETERS

TEST I-4 7/13/76 (MINUS 1" DRY)
MINUS 1.5" MUCK: 1" VIBE SCREEN
SAMPLE #1

MESH	PERCENT	SUM %
1.000/ 0.750	15.40	15.4
0.750/ 0.525	13.20	28.6
0.525/ 0.371	13.20	41.8
0.371/ 8	25.50	67.3
8/ 18	9.10	76.4
18/ 35	6.80	83.2
35/ 70	7.80	91.0
70/PAN	9.00	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =8.7943E+00 MM
COEFF. OF VARIATION = 87.77169
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 8.980040) ** 0.603445)
SLOPE = 0.603445 INTERCEPT B = 8.98003972000 MILLIMETERS
CORRELATION COEFF. = 0.992019 D50 = 7.16 MILLIMETERS

TABLE B-4.
Capacity Test Data

DATE July 13, 1976

TEST I-4

DURATION OF TEST 1.25 hr.

INPUT MATERIAL

Pipeline Muck: C dry
No. of Screen Analyses: 3
Average Moisture(%): Not reported

GENERAL CONDITIONS

Avg. Air Temp.(°F): 75
Avg. Barometric Pres(mmHg): 603.8
Avg. Relative Humidity%: 60

VARIABLE / SYNTRON SETTING(%)

VARIABLE	0	10	20	25	30	
Muck Throughput(stph)	0	11	27.8	36.5	46	
Crusher (hp)	17.0	20.1	18.4	20.1	20.7	
Feeder (hp)	-	6.8	9.7	11.0	11.3	
Blower (hp)	178.6	211.3	234.4	310.6	343.3	
Total Power(hp)	195.7	238.3	262.4	341.7	375.2	
Power Factor(%)	59	64	64	74	75	
Pipe Air Temp(°F)	137	150	162	198	210	
Line Air Pressure(psig)	4.35	5.64	6.21	8.95	10.1	
Kw-hr/S.Ton-1000 ft.	-	27.5	11.1	11.1	9.85	

TEST I-4 7/13/76 (MINUS 1" DRY)
MINUS 1.5" MUCK: 1" VIBE SCREEN
SAMPLE #2

MESH	PERCENT	SUM %
0.500/ 0.371	9.60	9.6
0.371/ 4	13.00	22.6
4/ 8	14.00	36.6
8/ 18	17.20	53.8
18/ 35	18.90	72.7
35/ 70	7.80	80.5
70/140	10.20	90.7
140/PAN	9.30	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =2.9319E+00 MM
COEFF. OF VARIATION = 118.02762
REYNOLDS NUMBER OF SETTLING = 1360.28 TEMP = 30.0 C
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 2.403459) ** 0.678413)
SLOPE = 0.678413 INTERCEPT B = 2.40345910000 MILLIMETERS
CORRELATION COEFF. = 0.992808 D50 = 1.23 MILLIMETERS

TEST I-4 7/13/76 (MINUS 1" DRY)
MINUS 1.5" MUCK: 1" VIBE SCREEN
SAMPLE #3

MESH	PERCENT	SUM %
1.000/ 0.371	22.90	22.9
0.371/ 4	20.30	43.2
4/ 18	26.20	69.4
18/ 35	10.10	79.5
35/ 50	6.50	86.0
50/ 70	4.20	90.2
70/140	6.10	96.3
140/PAN	3.70	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =6.2740E+00 MM
COEFF. OF VARIATION = 103.73621
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 4.802280) ** 0.736422)
SLOPE = 0.736422 INTERCEPT B = 4.80228043000 MILLIMETERS
CORRELATION COEFF. = 0.974954 D50 = 3.74 MILLIMETERS

TABLE B-5.
Capacity Test Data

DATE July 14,1976

TEST I-5

DURATION OF TEST 1.3 hr.

INPUT MATERIAL

Pipeline Muck: C moist
No. of Screen Analyses: 2
Average Moisture(%): Not Reported

GENERAL CONDITIONS

Avg. Air Temp(°F): 82
Avg. Barometric Pres(mmHg): 604.3
Avg. Relative Humidity %: 39.5

VARIABLE	**SYNTRON SETTING(%)**					
	15	10	20	35	40	
Muck Throughput(stph)	0	15.4	33	63	74	
Crusher (hp)	13.3	19.8	17.7		20.5	
Feeder (hp)	9.5	9.4	9.1	9.8	9.9	
Blower (hp)	181.8	196.3	213.5	268.7	318.1	
Total Power(hp)	204.6	225.5	240.3		348.5	
Power Factor(%)	57	59	62	70	74	
Pipe Air Temp(°F)	148	162	169	169	217	
Line Air Pressure(psig)	4.4	5.0	5.8	7.4	9.4	
Kw-hr/S.Ton-1000 ft.	-	16.8	8.54	5.60	5.67	

TEST I-5 7/14/76 (MINUS 1" MOIST)
MINUS 1.5" MUCK: 1" VIBE SCREEN
SAMPLE #1

MESH	PERCENT	SUM %
1.000/ 0.750	17.60	17.6
0.750/ 0.525	19.70	37.3
0.525/ 0.371	9.10	46.4
0.371/ 4	11.20	57.6
4/ 8	7.30	64.9
8/ 28	16.50	81.4
28/ 65	11.40	92.8
65/PAN	7.20	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =9.4853E+00 MM
COEFF. OF VARIATION = 86.48975
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 10.976426) ** 0.615100)
SLOPE = 0.615100 INTERCEPT B = 10.97642600000 MILLIMETERS
CORRELATION COEFF. = 0.986206 D50 = 7.91 MILLIMETERS

TEST I-5 7/14/76 (MINUS 1" MOIST)
MINUS 1.5" MUCK: 1" VIBE SCREEN
SAMPLE #2

MESH	PERCENT	SUM %
1.000/ 0.750	17.90	17.9
0.750/ 0.525	16.90	34.8
0.525/ 0.371	10.00	44.8
0.371/ 4	10.70	55.5
4/ 8	7.50	63.0
8/ 28	15.80	78.8
28/ 65	12.20	91.0
65/PAN	9.00	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =9.1675E+00 MM
COEFF. OF VARIATION = 90.14838
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 10.357913) ** 0.571055)
SLOPE = 0.571055 INTERCEPT B = 10.35791280000 MILLIMETERS
CORRELATION COEFF. = 0.987319 D50 = 7.14 MILLIMETERS

TABLE B-6.
Capacity Test Data

DATE July16, 1976

TEST I-6

DURATION OF TEST 0.98 hr.

INPUT MATERIAL

Pipeline Muck: D moist
No. of Screen Analyses: 1
Average Moisture(%): 3.7

GENERAL CONDITIONS

Avg. Air Temp.(°F): 92
Avg. Barometric Pres(mmHg): 607.6
Avg. Relative Humidity %: 22

VARIABLE	SYNTRON SETTING (%) 0	16	31	45		
Muck Throughput(stph)	-	29	60	89		
Crusher (hp)	15.6	16.0	16.1	17.4		
Feeder (hp)	7.9	9.5	9.1	11.3		
Blower (hp)	174.9	219.9	264.4	345.4		
Total Power (hp)	198.3	245.4	289.6	374.1		
Power Factor (%)	57	65	70	78		
Pipe Air Temp (°F)	159	176	195	228		
Line Air Pressure(psig)	4.3	6.0	7.4	10.4		
Kw-hr/S.Ton-1000 ft.	-	10.0	5.81	5.12		

IEST I-6 7/16/76 (MINUS 1.5" WET)
MINUS 1.5" MUCK: 1.5" VIBE SCREEN
SAMPLE #1

MESH	PERCENT	SUM %
1.000/ 0.525	13.30	13.3
0.525/ 0.371	8.30	21.6
0.371/ 4	15.20	36.8
4/ 8	12.50	49.3
8/ 28	21.40	70.7
28/ 65	16.90	87.6
65/100	4.20	91.8
100/PAN	8.20	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =5.4365E+00 MM
COEFF. OF VARIATION = 117.42946
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 4.431978) ** 0.662125)
SLOPE = 0.662125 INTERCEPT B = 4.43197787000 MILLIMETERS
CORRELATION COEFF. = 0.992544 D50 = 2.31 MILLIMETERS

TEST I-7 7/16/76 (MINUS 1.5" WET)
MINUS 1.5" MUCK: .5" VIBE SCREEN
SAMPLE #1

MESH	PERCENT	SUM %
1.000/ 0.525	18.80	18.8
0.525/ 0.371	9.50	28.3
0.371/ 4	15.00	43.3
4/ 8	11.10	54.4
8/ 28	19.70	74.1
28/ 65	15.40	89.5
65/100	3.60	93.1
100/PAN	6.90	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =6.5413E+00 MM
COEFF. OF VARIATION = 107.43890
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 5.795482) ** 0.658631)
SLOPE = 0.658631 INTERCEPT B = 5.79548240000 MILLIMETERS
CORRELATION COEFF. = 0.990930 D50 = 3.30 MILLIMETERS

TABLE B-7.
Capacity Test Data

DATE July 16, 1976

TEST I-7

DURATION OF TEST 0.47 hr.

INPUT MATERIAL

Pipeline Muck: D wet
No. of Screen Analyses: 2
Average Moisture(%): 4.3

GENERAL CONDITIONS

Avg. Air Temp.(F): 92
Avg. Barometric Pres(mmHg): 608.0
Avg. Relative Humidity %: 23

VARIABLE	SYNTRON SETTING (%)					
	12	31	45			
Muck Throughput (stph)	26	66	100			
Crusher (hp)	18.4	16.0	16.4			
Feeder (hp)	10.3	11.1	10.7			
Blower (hp)	208.1	254.3	338.5			
Total Power (hp)	236.8	281.4	365.6			
Power Factor (%)	63	72	78			
Pipe Air Temp (°F)	166	187	230			
Line Air Pressure (psig)	5.1	6.9	10.3			
Kw-hr/S.Ton-1000 ft.	10.6	5.09	4.47			

TEST I-7 7/16/76 (MINUS 1/5" WET)
MINUS 1.5" MUCK: .5" VIBE SCREEN
SAMPLE #2

MESH	PERCENT	SUM %
1.000/ 0.750	19.40	19.4
0.750/ 0.525	14.50	33.9
0.525/ 0.371	8.40	42.3
0.371/ 4	10.60	52.9
4/ 8	8.20	61.1
8/ 28	16.00	77.1
28/ 65	13.80	90.9
65/PAN	9.10	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =8.9573E+00 MM
COEFF. OF VARIATION = 94.20004
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 9.800641) ** 0.562639)
SLOPE = 0.562639 INTERCEPT B = 9.80064142000 MILLIMETERS
CORRELATION COEFF. = 0.987346 D50 = 6.01 MILLIMETERS

TEST I-8A 7/22/76 (MINUS 2" DRY)
MINUS 3"-1.5" BLEND MUCK: 1.5" VIBE SCREEN
SAMPLE #1

MESH	PERCENT	SUM %
1.500/ 0.525	18.60	18.6
0.525/ 0.371	12.70	31.3
0.371/ 4	18.50	49.8
4/ 8	13.00	62.8
8/ 28	20.10	82.9
28/ 65	14.20	97.1
65/100	1.70	98.8
100/PAN	1.20	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =8.3563E+00 MM
COEFF. OF VARIATION = 107.69692
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 6.606009) ** 1.009325)
SLOPE = 1.009325 INTERCEPT B = 6.60600877000 MILLIMETERS
CORRELATION COEFF. = 0.974403 D50 = 4.69 MILLIMETERS

TABLE B-8.
Capacity Test Data

DATE July 22, 1976

TEST I-8A

DURATION OF TEST 1.01 hr.

INPUT MATERIAL

Pipeline Muck: E moist
No. of Screen Analyses: 2
Average Moisture(%): Not reported

GENERAL CONDITIONS

Avg. Air Temp.(°F): 84
Avg. Barometric Pres(mmHg): 606.8
Avg. Relative Humidity%: 40

VARIABLE	SYNTRON SETTING(%)					
	10	20	30			
Muck Throughput(stph)	21	42	63			
Crusher (hp)	22.6*	22.8	26.8			
Feeder (hp)	12.5*	10.5	11.9			
Blower (hp)	242.0*	293.9	359.0			
Total Power(hp)	277.1*	327.2	397.7			
Power Factor(%)	67	74	78			
Pipe Air Temp(°F)	171	195	224			
Line Air Pressure(psig)	6.1	8.5	10.4			
Kw-hr/S.Ton-1000 ft.	15.2*	9.23	7.52			

* instantaneous readings

TEST I-8A 7/22/76 (MINUS 2" DRY)
MINUS 3"-1.5" BLEND MUCK: 1.5" VIBE SCREEN
SAMPLE #2

MESH	PERCENT	SUM %
1.500/ 0.525	17.99	18.0
0.525/ 0.371	16.90	34.9
0.371/ 4	17.60	52.5
4/ 8	10.60	63.1
8/ 28	14.41	77.5
28/ 65	12.50	90.0
65/100	4.40	94.4
100/PAN	5.60	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =8.4457E+00 MM
COEFF. OF VARIATION = 105.91416
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 7.299126) ** 0.664374)
SLOPE = 0.664374 INTERCEPT B = 7.29912645000 MILLIMETERS
CORRELATION COEFF. = 0.987081 D50 = 5.39 MILLIMETERS

TEST I-8B 7/19/76 (MINUS 2" DRY)
MINUS 3"-1.5" BLEND MUCK: 1.5" VIBE SCREEN
SAMPLE #1

MESH	PERCENT	SUM %
1.250/ 1.000	14.80	14.8
1.000/ 0.750	11.10	25.9
0.750/ 0.525	17.90	43.8
0.525/ 0.371	11.10	54.9
0.371/ 4	12.90	67.8
4/ 8	7.00	74.8
8/ 28	8.80	83.6
28/PAN	16.40	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =1.2197E+01 MM
COEFF. OF VARIATION = 80.22968
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 14.835693) ** 0.611738)
SLOPE = 0.611738 INTERCEPT B = 14.83569250000 MILLIMETERS
CORRELATION COEFF. = 0.960468 D50 = 11.15 MILLIMETERS

TABLE B-9.
Capacity Test Data

DATE July 19, 1976

TEST I-8B

DURATION OF TEST 0.9 hr.

INPUT MATERIAL

Pipeline Muck: E dry
No. of Screen Analyses: 1
Average Moisture(%): 0.9

GENERAL CONDITIONS

Avg. Air Temp.(°F): 71
Avg. Barometric Pres(mmHg): 604.8
Avg. Relative Humidity %: 74

VARIABLE | **SYNTRON SETTING(%)**

	10	20				
Muck Throughput(stph)	21	42				
Crusher (hp)	21.5	26.6				
Feeder (hp)	9.8	11.1				
Blower (hp)	273.0	333.1				
Total Power(hp)	304.3	370.8				
Power Factor(%)	70	77				
Pipe Air Temp(°F)	177	210				
Line Air Pressure(psig)	7.6	10.8				
Kw-hr/S.Ton-1000 ft.	17.2	10.5				

TABLE B-10
Capacity Test Data

DATE July 21, 1976

TEST I-9

DURATION OF TEST 1.01 hr.

INPUT MATERIAL

Pipeline Muck: E wet
No. of Screen Analyses: 4
Average Moisture(%): 5.1

GENERAL CONDITIONS

Avg. Air Temp.(°F): 74
Avg. Barometric Pres(mmHg): 605.5
Avg. Relative Humidity %: 60

VARIABLE | **SYNTRON SETTING(%)**

	20	30	41	40	21	10
Muck Throughput(stph)	47	69	92	90	48	25
Crusher (hp)	18.7*	21.3	19.8*	23.7	18.4	18.1
Feeder (hp)	10.7*	11.1	11.5*	11.1	9.5	9.3
Blower (hp)	202.5*	273.6	341.6*	327.7	219.9	215.6
Total Power(hp)	231.9*	306.0	372.9*	362.6	247.8	243.0
Power Factor(%)	61	73	74	77	63	62
Pipe Air Temp(°F)	-	184	201	203	163	160
Line Air Pressure(psig)	-	7.8	9.7	10.2	5.9	5.8
Kw-hr/S.Ton-1000 ft.	5.69*	5.24	4.90*	4.81	6.81	11.4

* Instantaneous reading

TEST I-9 7/21/76 (MINUS 2" WET)
MINUS 3"-1.5" BLEND MUCK: 1.5" VIBE SCREEN
SAMPLE #1

MESH	PERCENT	SUM %
1.250/ 0.750	15.99	16.0
0.750/ 0.525	20.90	36.9
0.525/ 0.371	11.30	48.2
0.371/ 4	11.00	59.2
4/ 8	6.30	65.5
8/ 28	14.30	79.8
28/ 65	13.11	92.9
65/PAN	7.10	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =1.0004E+01 MM
COEFF. OF VARIATION = 88.91947
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 11.019411) ** 0.610786)
SLOPE = 0.610786 INTERCEPT B = 11.01941110000 MILLIMETERS
CORRELATION COEFF. = 0.978347 D50 = 8.65 MILLIMETERS

TEST I-9 7/21/76 (MINUS 2" WET)
MINUS 3"-1.5" BLEND MUCK: 1.5" VIBE SCREEN
SAMPLE #2

MESH	PERCENT	SUM %
1.000/ 0.750	14.40	14.4
0.750/ 0.525	18.40	32.8
0.525/ 0.371	11.20	44.0
0.371/ 4	14.80	58.8
4/ 8	9.60	68.4
8/ 28	16.50	84.9
28/ 65	12.40	97.3
65/PAN	2.70	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =9.1381E+00 MM
COEFF. OF VARIATION = 84.31558
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 9.668596) ** 0.826866)
SLOPE = 0.826866 INTERCEPT B = 9.66859591000 MILLIMETERS
CORRELATION COEFF. = 0.977508 D50 = 7.52 MILLIMETERS

TEST I-9 7/21/76 (MINUS 2" WET)
MINUS 3"-1.5" BLEND MUCK: 1.5" VIBE SCREEN
SAMPLE #3

MESH	PERCENT	SUM %
1.000/ 0.750	24.00	24.0
0.750/ 0.525	14.90	38.9
0.525/ 0.371	11.40	50.3
0.371/ 4	12.60	62.9
4/ 8	8.80	71.7
8/ 28	13.70	85.4
28/ 65	10.00	95.4
65/PAN	4.60	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =1.0495E+01 MM
COEFF. OF VARIATION = 79.70254
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 13.274634) ** 0.684645)
SLOPE = 0.684645 INTERCEPT B = 13.27463400000 MILLIMETERS
CORRELATION COEFF. = 0.989370 D50 = 9.53 MILLIMETERS

TEST I-9 7/21/76 (MINUS 2" WET)
MINUS 3"-1.5" BLEND MUCK: 1.5" VIBE SCREEN
SAMPLE #4

MESH	PERCENT	SUM %
1.250/ 0.750	20.99	21.0
0.750/ 0.525	13.82	34.8
0.525/ 0.371	8.20	43.0
0.371/ 4	11.20	54.2
4/ 8	8.20	62.4
8/ 28	15.40	77.8
28/ 65	13.99	91.8
65/PAN	8.20	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =9.8777E+00 MM
COEFF. OF VARIATION = 96.94627
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 10.361419) ** 0.575033)
SLOPE = 0.575033 INTERCEPT B = 10.36141910000 MILLIMETERS
CORRELATION COEFF. = 0.986275 D50 = 6.49 MILLIMETERS

WEAR TEST - 1976

8/13/76 (MINUS 1.5" DRY)
1.5" VIBE SCREEN
TIME: 1600

MESH	PERCENT	SUM %
1.500/ 0.750	13.80	13.8
0.750/ 0.525	17.10	30.9
0.525/ 0.371	6.70	37.6
0.371/ 4	14.20	51.8
4/ 8	9.50	61.3
8/ 28	15.40	76.7
28/ 60	12.30	89.0
60/PAN	11.00	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =9.1089E+00 MM
COEFF. OF VARIATION = 105.23133
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 8.294166) ** 0.578997)
SLOPE = 0.578997 INTERCEPT B = 8.29416633000 MILLIMETERS
CORRELATION COEFF. = 0.988472 D50 = 5.32 MILLIMETERS

8/14/76 (MINUS 1.5" DRY)
1.5" VIBE SCREEN

MESH	PERCENT	SUM %
1.500/ 0.750	17.80	17.8
0.750/ 0.525	12.90	30.7
0.525/ 0.371	8.20	38.9
0.371/ 4	12.30	51.2
4/ 8	11.30	62.5
8/ 28	11.50	74.0
28/ 60	13.50	87.5
60/PAN	12.50	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =9.6211E+00 MM
COEFF. OF VARIATION = 106.54061
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 8.903688) ** 0.527851)
SLOPE = 0.527851 INTERCEPT B = 8.90368784000 MILLIMETERS
CORRELATION COEFF. = 0.988262 D50 = 5.18 MILLIMETERS

8/24/76
MINUS .5" MUCK: 1" VIBE SCREEN

MESH	PERCENT	SUM %
1.000/ 0.750	14.70	14.7
0.750/ 0.525	13.80	28.5
0.525/ 0.371	9.60	38.1
0.371/ 4	12.20	50.3
4/ 8	13.40	63.7
8/ 28	9.60	73.3
28/ 60	14.50	87.8
60/PAN	12.20	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =8.1500E+00 MM
COEFF. OF VARIATION = 97.25780
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 8.184749) ** 0.548498)
SLOPE = 0.548498 INTERCEPT B = 8.18474853000 MILLIMETERS
CORRELATION COEFF. = 0.984089 D50 = 4.84 MILLIMETERS

8/24/76 (.75" WET)
1" VIBE SCREEN
SAMPLE #1

MESH	PERCENT	SUM %
1.500/ 0.525	14.90	14.9
0.525/ 0.371	12.20	27.1
0.371/ 4	8.50	35.6
4/ 8	10.50	46.1
8/ 16	11.60	57.7
16/ 28	11.40	69.1
28/ 60	17.00	86.1
60/PAN	13.90	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =6.5670E+00 MM
COEFF. OF VARIATION = 133.81587
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 4.336754) ** 0.565644)
SLOPE = 0.565644 INTERCEPT B = 4.33675444000 MILLIMETERS
CORRELATION COEFF. = 0.978277 D50 = 1.91 MILLIMETERS

8/24/76 (.75" WET)
1" VIBE SCREEN
SAMPLE #2

MESH	PERCENT	SUM %
1.000/ 0.525	10.90	10.9
0.525/ 0.371	10.90	21.8
0.371/ 4	12.60	34.4
4/ 8	7.40	41.8
8/ 16	13.70	55.5
16/ 28	14.50	70.0
28/ 60	13.10	83.1
60/PAN	16.90	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =4.9255E+00 MM
COEFF. OF VARIATION = 125.93912
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 3.610534) ** 0.571738)
SLOPE = 0.571738 INTERCEPT B = 3.61053380000 MILLIMETERS
CORRELATION COEFF. = 0.988034 D50 = 1.54 MILLIMETERS

10/5/76 MOISTURE CONTENT= 2.35%

MESH	PERCENT	SUM %
1.500/ 1.000	10.32	10.3
1.000/ 0.750	36.77	47.1
0.750/ 0.525	14.49	61.6
0.525/ 0.371	6.23	67.8
0.371/ 4	7.61	75.4
4/ 10	9.16	84.6
10/ 35	7.72	92.3
35/PAN	7.70	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =1.5430E+01 MM
COEFF. OF VARIATION = 64.30521
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 23.502689) ** 0.677306)
SLOPE = 0.677306 INTERCEPT B = 23.50268910000 MILLIMETERS
CORRELATION COEFF. = 0.932051 D50 = 17.90 MILLIMETERS

10/7/76 MOISTURE CONTENT= 2.06%
SAMPLE #1

MESH	PERCENT	SUM %
1.500/ 1.000	3.59	3.6
1.000/ 0.750	21.13	24.7
0.750/ 0.375	48.45	73.2
0.375/ 4	10.76	83.9
4/ 8	3.26	87.2
8/ 14	1.81	89.0
14/ 35	3.44	92.4
35/PAN	7.56	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =1.3716E+01 MM
COEFF. OF VARIATION = 55.18667
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 16.663898) ** 0.842537)
SLOPE = 0.842537 INTERCEPT B = 16.66389750000 MILLIMETERS
CORRELATION COEFF. = 0.903606 D50 = 14.08 MILLIMETERS

10/7/76 MOISTURE CONTENT= 2.06%
SAMPLE #2

MESH	PERCENT	SUM %
1.500/ 1.000	3.62	3.6
1.000/ 0.750	27.90	31.5
0.750/ 0.525	28.45	60.0
0.525/ 0.371	15.98	76.0
0.371/ 4	8.48	84.4
4/ 10	3.77	88.2
10/ 35	4.68	92.9
35/PAN	7.12	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =1.4559E+01 MM
COEFF. OF VARIATION = 54.22433
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 20.155509) ** 0.801197)
SLOPE = 0.801197 INTERCEPT B = 20.15550880000 MILLIMETERS
CORRELATION COEFF. = 0.886857 D50 = 15.34 MILLIMETERS

10/8/76 MOISTURE CONTENT= 3.07%

MESH	PERCENT	SUM %
1.500/ 1.000	3.60	3.6
1.000/ 0.750	11.35	15.0
0.750/ 0.525	17.34	32.3
0.525/ 0.371	13.71	46.0
0.371/ 4	15.88	61.9
4/ 10	11.97	73.9
10/ 35	13.33	87.2
35/PAN	12.80	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =9.7028E+00 MM
COEFF. OF VARIATION = 86.68240
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 8.856532) ** 0.715925)
SLOPE = 0.715925 INTERCEPT B = 8.85653186000 MILLIMETERS
CORRELATION COEFF. = 0.968194 D50 = 8.24 MILLIMETERS

10/12/76 MOISTURE CONTENT= 7.04%

MESH	PERCENT	SUM %
0.750/ 0.525	1.51	1.5
0.525/ 0.371	1.62	3.1
0.371/ 4	9.05	12.2
4/ 10	27.67	39.8
10/ 20	25.10	64.9
20/ 35	20.57	85.5
35/ 48	4.95	90.5
48/ 65	2.86	93.3
65/PAN	6.66	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =2.4237E+00 MM
COEFF. OF VARIATION = 116.70311
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 2.510691) ** 1.002298)
SLOPE = 1.002298 INTERCEPT B = 2.51069090000 MILLIMETERS
CORRELATION COEFF. = 0.991337 D50 = 1.32 MILLIMETERS

10/14/76 MOISTURE CONTENT= 0.64%

MESH	PERCENT	SUM %
1.500/ 1.000	44.30	44.3
1.000/ 0.750	42.34	86.6
0.750/ 0.525	7.93	94.6
0.525/ 0.371	1.57	96.1
0.371/ 4	1.25	97.4
4/ 10	0.42	97.8
10/ 35	0.46	98.3
35/PAN	1.73	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =2.5048E+01 MM
COEFF. OF VARIATION = 28.73261
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/303.031372) ** 0.710682)
SLOPE = 0.710682 INTERCEPT B =303.03137200000 MILLIMETERS
CORRELATION COEFF. = 0.777336 D50 = 24.55 MILLIMETERS

11/4/76 MOISTURE CONTENT= 2.48%
TIME: 1410

MESH	PERCENT	SUM %
1.500/ 1.000	14.41	14.4
1.000/ 0.750	22.67	37.1
0.750/ 0.525	15.98	53.1
0.525/ 0.371	13.10	66.2
0.371/ 4	11.97	78.1
4/ 10	7.97	86.1
10/ 35	7.24	93.3
35/PAN	6.66	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =1.4881E+01 MM
COEFF. OF VARIATION = 67.70961
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 20.401769) ** 0.747034)
SLOPE = 0.747034 INTERCEPT B = 20.40176940000 MILLIMETERS
CORRELATION COEFF. = 0.966724 D50 = 14.43 MILLIMETERS

11/4/76 MOISTURE CONTENT= 2.6%
TIME: 1516

MESH	PERCENT	SUM %
1.500/ 1.000	18.40	18.4
1.000/ 0.750	27.78	46.2
0.750/ 0.525	12.46	58.6
0.525/ 0.371	8.44	67.1
0.371/ 4	8.54	75.6
4/ 10	7.15	82.8
10/ 35	9.95	92.7
35/PAN	7.28	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =1.5944E+01 MM
COEFF. OF VARIATION = 67.89737
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 25.231539) ** 0.653699)
SLOPE = 0.653699 INTERCEPT B = 25.23153900000 MILLIMETERS
CORRELATION COEFF. = 0.961718 D50 = 17.30 MILLIMETERS

11/19/76 NO MOISTURE CONTENT TAKEN
TIME: 1500

MESH	PERCENT	SUM %
1.500/ 1.000	16.41	16.4
1.000/ 0.750	18.61	35.0
0.750/ 0.525	6.29	41.3
0.525/ 0.371	8.02	49.3
0.371/ 4	11.09	60.4
4/ 10	12.60	73.0
10/ 35	17.39	90.4
35/PAN	9.59	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =1.2663E+01 MM
COEFF. OF VARIATION = 90.34430
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 14.044659) ** 0.629569)
SLOPE = 0.629569 INTERCEPT B = 14.04465910000 MILLIMETERS
CORRELATION COEFF. = 0.987808 D50 = 9.14 MILLIMETERS

7/26/77 MOISTURE CONTENT= 2.77%
.75" MUCK: 1" VIBE SCREEN
TIME: 1648

MESH	PERCENT	SUM %
1.000/ 0.750	2.52	2.5
0.750/ 0.525	23.21	25.7
0.525/ 0.371	21.86	47.6
0.371/ 4	17.90	65.5
4/ 10	17.22	82.7
10/ 20	4.77	87.5
20/ 35	3.27	90.8
35/ 60	1.99	92.7
60/PAN	7.26	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =8.7163E+00 MM
COEFF. OF VARIATION = 69.24812
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 8.903557) ** 0.804875)
SLOPE = 0.804875 INTERCEPT B = 8.90355742000 MILLIMETERS
CORRELATION COEFF. = 0.964265 D50 = 8.79 MILLIMETERS

7/26/77 MOISTURE CONTENT= 2.91%
.75" MUCK: 1" VIBE SCREEN
TIME: 1808

MESH	PERCENT	SUM %
1.000/ 0.750	3.88	3.9
0.750/ 0.525	21.23	25.1
0.525/ 0.371	20.70	45.8
0.371/ 4	16.88	62.7
4/ 10	16.27	79.0
10/ 20	5.66	84.6
20/ 35	4.87	89.5
35/ 60	3.13	92.6
60/PAN	7.38	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =8.4885E+00 MM
COEFF. OF VARIATION = 74.31053
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 8.541194) ** 0.767445)
SLOPE = 0.767445 INTERCEPT B = 8.54119360000 MILLIMETERS
CORRELATION COEFF. = 0.974835 D50 = 8.26 MILLIMETERS

7/27/77 MOISTURE CONTENT= 1.75%
.75" MUCK: 1" VIBE SCREEN
TIME: 1552

MESH	PERCENT	SUM %
0.525/ 0.525	7.93	7.9
0.525/ 0.371	23.39	31.3
0.371/ 4	23.18	54.5
4/ 10	22.85	77.4
10/ 20	6.75	84.1
20/ 35	4.67	88.8
35/ 60	3.15	91.9
60/PAN	8.08	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =6.2207E+00 MM
COEFF. OF VARIATION = 71.42020
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 6.764295) ** 0.797146)
SLOPE = 0.797146 INTERCEPT B = 6.76429457000 MILLIMETERS
CORRELATION COEFF. = 0.983466 D50 = 5.64 MILLIMETERS

7/28/77 MOISTURE CONTENT= 2.41%
.75" MUCK: 1" VIBE SCREEN
NO TIME

MESH	PERCENT	SUM %
1.000/ 0.750	0.66	0.7
0.750/ 0.525	12.00	12.7
0.525/ 0.371	20.35	33.0
0.371/ 4	21.14	54.2
4/ 10	20.63	74.8
10/ 20	6.69	81.5
20/ 35	5.29	86.8
35/ 60	4.16	90.9
60/PAN	9.09	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =6.6998E+00 MM
COEFF. OF VARIATION = 80.36700
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 5.552165) ** 0.816235)
SLOPE = 0.816235 INTERCEPT B = 5.55216515000 MILLIMETERS
CORRELATION COEFF. = 0.972451 D50 = 5.65 MILLIMETERS

7/28/77 MOISTURE CONTENT= 1.00%
.75" MUCK: 1" VIBE SCREEN
NO TIME

MESH	PERCENT	SUM %
1.000/ 0.750	0.53	0.5
0.750/ 0.525	14.38	14.9
0.525/ 0.371	21.83	36.7
0.371/ 4	20.47	57.2
4/ 10	19.94	77.2
10/ 20	5.97	83.1
20/ 35	4.75	87.9
35/ 60	3.68	91.5
60/PAN	8.45	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =7.1410E+00 MM
COEFF. OF VARIATION = 76.68707
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 6.018416) ** 0.829868)
SLOPE = 0.829868 INTERCEPT B = 6.01841575000 MILLIMETERS
CORRELATION COEFF. = 0.966273 D50 = 6.38 MILLIMETERS

7/30/77 MOISTURE CONTENT= 1.91%
.75" MUCK: 1" VIBE SCREEN
TIME: 0905

MESH	PERCENT	SUM %
1.000/ 0.750	0.62	0.6
0.750/ 0.525	12.70	13.3
0.525/ 0.371	16.27	29.6
0.371/ 4	19.63	49.2
4/ 10	21.83	71.1
10/ 20	7.54	78.6
20/ 35	5.85	84.4
35/ 60	4.40	88.8
60/PAN	11.16	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =6.2888E+00 MM
COEFF. OF VARIATION = 87.19132
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 4.993359) ** 0.770704)
SLOPE = 0.770704 INTERCEPT B = 4.99335915000 MILLIMETERS
CORRELATION COEFF. = 0.973020 D50 = 4.61 MILLIMETERS

7/30/77 MOISTURE CONTENT= 1.00%
.75" MUCK: 1" VIBE SCREEN
TIME: 1017

MESH	PERCENT	SUM %
0.525/ 0.525	3.57	3.6
0.525/ 0.371	11.19	14.8
0.371/ 4	17.62	32.4
4/ 10	25.28	57.7
10/ 20	12.31	70.0
20/ 35	9.88	79.9
35/ 60	6.65	86.5
60/PAN	13.50	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =4.0553E+00 MM
COEFF. OF VARIATION = 98.68979
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 3.415069) ** 0.738439)
SLOPE = 0.738439 INTERCEPT B = 3.41506919000 MILLIMETERS
CORRELATION COEFF. = 0.995482 D50 = 2.58 MILLIMETERS

7/30/77 MOISTURE CONTENT= 3.27%
.75" MUCK: 1" VIBE SCREEN
TIME: 1248

MESH	PERCENT	SUM %
1.000/ 0.750	2.40	2.4
0.750/ 0.525	3.25	5.7
0.525/ 0.371	8.97	14.6
0.371/ 4	13.10	27.7
4/ 10	26.01	53.7
10/ 20	13.38	67.1
20/ 35	11.03	78.1
35/ 60	7.49	85.6
60/PAN	14.37	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =4.1141E+00 MM
COEFF. OF VARIATION = 120.36984
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 3.209860) ** 0.709126)
SLOPE = 0.709126 INTERCEPT B = 3.20985961000 MILLIMETERS
CORRELATION COEFF. = 0.998797 D50 = 2.09 MILLIMETERS

8/2/77 MOISTURE CONTENT= 4.61%
.75" MUCK: 1" VIBE SCREEN
TIME: 1402

MESH	PERCENT	SUM %
1.000/ 0.750	1.19	1.2
0.750/ 0.525	7.28	8.5
0.525/ 0.371	12.66	21.1
0.371/ 4	18.67	39.8
4/ 10	25.41	65.2
10/ 20	11.37	76.6
20/ 35	9.72	86.3
35/ 60	4.60	90.9
60/PAN	9.10	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =5.2433E+00 MM
COEFF. OF VARIATION = 97.27088
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 4.386542) ** 0.827891)
SLOPE = 0.827891 INTERCEPT B = 4.38654190000 MILLIMETERS
CORRELATION COEFF. = 0.994726 D50 = 3.49 MILLIMETERS

8/2/77 MOISTURE CONTENT= 6.62%
.75" MUCK: 1" VIBE SCREEN
TIME: 1505

MESH	PERCENT	SUM %
1.000/ 0.750	2.49	2.5
0.750/ 0.525	9.64	12.1
0.525/ 0.371	14.97	27.1
0.371/ 4	19.34	46.4
4/ 10	23.65	70.1
10/ 20	11.11	81.2
20/ 35	8.53	89.7
35/ 60	3.79	93.5
60/PAN	6.53	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =6.1520E+00 MM
COEFF. OF VARIATION = 91.09169
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 5.537314) ** 0.867140)
SLOPE = 0.867140 INTERCEPT B = 5.53731436000 MILLIMETERS
CORRELATION COEFF. = 0.996001 D50 = 4.26 MILLIMETERS

8/5/77 MOISTURE CONTENT= 3.66%
.75" MUCK: 1" VIBE SCREEN
TIME: 0955

MESH	PERCENT	SUM %
1.000/ 0.750	0.36	0.4
0.750/ 0.525	7.86	8.2
0.525/ 0.371	17.45	25.7
0.371/ 4	20.73	46.4
4/ 10	21.54	67.9
10/ 20	10.06	78.0
20/ 35	9.51	87.5
35/ 60	3.84	91.4
60/PAN	8.65	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =5.6995E+00 MM
COEFF. OF VARIATION = 88.18028
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 4.542808) ** 0.861245)
SLOPE = 0.861245 INTERCEPT B = 4.54280776000 MILLIMETERS
CORRELATION COEFF. = 0.984145 D50 = 4.21 MILLIMETERS

8/5/77 MOISTURE CONTENT= 2.99%
.75" MUCK: 1" VIBE SCREEN
TIME: 1417

MESH	PERCENT	SUM %
1.000/ 0.750	9.75	9.8
0.750/ 0.525	5.58	15.3
0.525/ 0.371	10.11	25.4
0.371/ 4	14.50	39.9
4/ 10	20.48	60.4
10/ 20	10.86	71.3
20/ 35	9.61	80.9
35/ 60	6.82	87.7
60/PAN	12.29	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =6.1324E+00 MM
COEFF. OF VARIATION = 112.77314
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 5.153370) ** 0.635859)
SLOPE = 0.635859 INTERCEPT B = 5.15337008000 MILLIMETERS
CORRELATION COEFF. = 0.998350 D50 = 3.21 MILLIMETERS

8/6/77 MOISTURE CONTENT= 1.79%
.75" MUCK: 1" VIBE SCREEN
TIME: 0852

MESH	PERCENT	SUM %
1.000/ 0.750	0.51	0.5
0.750/ 0.525	5.42	5.9
0.525/ 0.371	14.28	20.2
0.371/ 4	23.01	43.2
4/ 10	23.67	66.9
10/ 20	9.07	76.0
20/ 35	6.71	82.7
35/ 60	4.95	87.6
60/PAN	12.38	100.0
TOTAL =	100.00	

WEIGHTED MEAN DIAMETER =5.1846E+00 MM
COEFF. OF VARIATION = 91.35613
ROSIN - RAMMLER EQ.: R = 100 * EXP(-(D/ 3.966178) ** 0.792874)
SLOPE = 0.792874 INTERCEPT B = 3.96617830000 MILLIMETERS
CORRELATION COEFF. = 0.982668 D50 = 3.84 MILLIMETERS

APPENDIX C

WEIGHTS IN KG FOR BEND LINERS FOR 1977 WEAR TEST

Loca-tion	Liner	Initial	Final	Loss 1st 5 hrs.	Loss 2nd 5 hrs.	Liner	Initial	Final
			30° FLATBACK BEND					
#2	A-10	15.466	15.294	0.152	0.133	A-10	15.294	15.161
#3*	#61	15.447	14.720	0.727+	1.239	#72+	10.401	9.162+
	#51	13.880	13.477	0.403			0.403	
#4*	#56	14.050	12.888	1.162	1.567	#71+	10.186	8.619+
	#62	15.660	14.816	0.844	1.567			
#5	#54	13.707	12.954	0.753	0.545	#54	12.954	12.409
#6	#55	13.831	13.642	0.189	0.142	#55	13.642	13.500
			90° FLATBACK BEND					
#1	B-17*	15.410	15.416	-	0.066	C-19	15.306	15.240
#2	B-15*	14.980	14.810	0.170	0.222	C-20	15.407	15.185
#3	C-22*	15.492	14.768	0.724	0.316	C-16	15.488	15.172
#4	B-11*	15.138	14.381	0.757	0.940	C-13	15.177	14.237
#5	C-17*	15.004	14.382	0.622	0.499	C-21	16.528	16.029
#6	B-12*	15.252	14.934	0.318	0.663	C-12	15.522	14.859
#7	#41*	3.433	3.353	0.080	0.087	#41	3.353	3.266
#8	#42*	3.490	3.435	0.055	0.029	#42	3.435	3.406
#9	#43*	3.444	3.401	0.043	0.030	#43	3.401	3.371
#10	#52	14.241	14.090	0.151	0.068	#52	14.090	14.022
#11	#53	13.885	13.766	0.119	0.065	#53	13.766	13.701

*Removed after 2 hr.& 40 min. run.
Worn to a point where #4(62) was about to wear through in 2 hrs; rotated & put 40 more min. on liners before replacing with cast iron #51 & #56. Cast iron wore through in 2 hr. & 20 min-possibility of casting flaw.

+ Worn through @ 2 hr. 42 min. but on rotation didn't go after 2 hr. 20 min.

1977 WEAR TEST (Cont'd.)

End of Test - last 9 hrs.

Location	Liner	Start Weight kg	End Weight kg	Weight Loss kg
		30^{o} FLATBACK BEND		
#2	B-16	15.054	14.838	0.216
#3	B-19	14.655	13.944	0.711
	#41	-	-	-
#4	C-18	16.515	14.892	1.623
	#44	3.447	3.385	0.062
#5	#54	12.409	11.774	0.635
#6	#55	13.500	13.232	0.268
		90^{o} FLATBACK BEND		
#1	B-17	15.410	15.367	0.043
#2	B-15	14.810	14.573	0.237
#3	C-22	14.768	13.881	0.887
#4	B-11	14.381	13.413	0.968
#5	C-17	14.382	13.532	0.850
#6	B-12	14.934	14.558	0.376
#7	#41	3.266	2.945	0.321
#8	#42	3.406	3.340	0.054
#9	#43	3.371	3.338	0.033
#10	#52	14.022	13.883	0.139
#11	#53	13.701	13.542	0.159
#7	A-10	15.161	15.022	0.139

Note: After 6 hr., 37 min., liners B-19, C-18 in 30^{o} Bend were badly worn. They were replaced by #41 from 90^{o} bend and #44 which had not been previously used. Liner A-10 replaced #41 in 90^{o} bend for remaining 2-1/2 hours.

APPENDIX D

REPORT OF NEW TECHNOLOGY

The findings of this study, as reported herein, are primarily based upon the utilization of commercially available equipment for the transportation of tunnel muck via a pipeline.

The objective of the study was to evaluate a pneumatic pipeline system for muck haulage from a tunnel excavated by a tunnel boring machine. The system was comprised of a muck preparation unit, solids feeder and air blower, telescoping pipes and 500 feet of 10-inch diameter pipe. The system transported up to 100 tph of simulated tunnel muck with maximum sizes ranging from 1/2-inch to more than 3 inches. The system components were tested for reliability and flexibility, wear and maintenance requirements, capacity, noise and dust levels, effect of moisture content, extensibility, and power requirements.

This system has no previously known application in U.S. tunneling construction; it is in use in the coal industry and has been used in one Canadian tunnel project. The results of the study indicate such a system to be feasible and reliable, with the exception of elbow wear in the pipeline.

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