REVIEW OF RUSSIAN DATA ON HYDROTRANSPORT OF COAL

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16. Abstract

A review was made of two Russian books and a chapter from a third book dealing with pipeline transport of coal. Emphasis was placed on hydrotransport of coarse coal in underground mines or surface pipelines. The books reviewed were: "Means of Increasing the Effectiveness of Hydrotransport," by V. N. Pokrovskaya (1972), "Parameters and Modes of Hydraulic Transport of Coal" by V. V. Traynis (1970), and the chapter "Calculations of Hydrotransport of Useful Minerals and Waste Rock" from the book "Hydromechanization of Opencast Workings" by G. A. Nurok (1970). All three are unique and useful additions to the world literature on hydrotransport. The Traynis book reveals the development and results of circular wheel stand tests to simulate hydrotransport in horizontal pipes, which is a potentially outstanding contribution to slurry pipeline technology. Graphical data and equations are presented which suggest that headlosses for coarse coal can be predicted with good accuracy for pipe sizes up to 14 inches in diameter. Wheel stands permit tests for pipe wear and lump degradation without recycling coal through pumps. Recommendations are made for wheel stand tests and for correlation of existing data.

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FOREWORD

This report was prepared by Terraspace, Inc., under USBM Contract Number J0265016. The contract was initiated under the Advancing Coal Mining Technology Program. It was administered under the technical direction of the Twin Cities Mining Research Center, with Mr. John W. Chester acting as the Technical Project Officer. Mr. David W. Askin was the contract administrator for the Bureau of Mines.

This report is a summary of the work recently completed as part of this contract during the period August 1, 1976 to November 30, 1976. This report was submitted by the authors on December 15, 1976.

Consultation on this report was provided by Prof. Robert R. Faddick of the Colorado School of Mines. This report is one of three reports under the contract. The other two are entitled, "Survey of Surface Hydraulic Mining Technology" and "Survey of Coal Preparation Technology for Hydraulic Coal Mines".

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EXECUTIVE SUMMARY

Reviews are presented of two Russian books and a chapter of a third book which relate to slurry hydrotransport. Primary emphasis is placed on data relating to hydrotransport of coal. All three volumes represent unique and outstanding contributions to the world literature on slurry transport and exhibit the importance and extensive effort devoted to this field in the USSR. The significance of these books is related not only to pipeline transport of coal from mines to power plants or beneficiation plants but slurry transport in general. The ultimate applications may include systems incorporating hydraulic mines, slurry pipelines and direct combustion of coal slurry in boilers.

The Traynis book discusses the use of wheel stands (rotating doughnut-shaped pipes, partially filled with slurry) as an economical means for obtaining data on headloss, deposition velocity, lump degradation and erosive wear. Further development and application of wheel stands is recommended as a useful research method.

Russian developments of large centrifugal coal pumps indicate that this technology may be applicable for long distance coal slurry pipelines to replace reciprocating pumps which require high maintenance and are not applicable for coarse coal.

I. INTRODUCTION

In recent years, increasing research and development effort has been devoted to hydraulic transport of coal. Long distance pipelining of finely ground coal slurry has been successfully accomplished in the United States in the Ohio pipeline (Ref.1) and the Black Mesa Pipeline (Ref.2,3). Development of hydrotransport of coarse coal in underground coal mines is underway by Continental Oil Co. (Ref.4,5). However, these U.S. developments have been privately funded and, therefore, detailed technical data have not been published.

The U.S. Bureau of Mines has increased its research and development related to hydraulic coal mining and hydraulic transport. Plans for a coal hydrotransport research facility at Bruceton, Pennsylvania, are nearing completion.

Under contracts to the Bureau of Mines (Ref.6,7,8), Terraspace, Inc. has translated to English many Russian publications relating to hydrotransport and has provided copies as part of a Survey Library on Hydraulic Mining located at the USBM Twin Cities Mining Research Center. Three of these Russian publications (Ref. 9,10,11) were considered especially signficant. Therefore, the purpose of this report is to review these three documents for the purpose of evaluating their relevance to United States engineering practice and to make recommendations for future experimental or analytical research on coarse coal hydrotransport.

II. GENERAL REVIEW

II.1 REVIEW OF BOOK BY V. N. POKROVSKAYA, "MEANS OF INCREASING THE EFFECTIVENESS OF HYDROTRANSPORT" (1972)

This book (Ref.10) contains an Introduction and seven chapters which are reviewed below.

II.1.0 Introduction

The Introduction contains useful facts pertaining to hydrotransport practice in the USSR. For example:

1. The water consumption for hydrotransport is
   For coal: 10 to 15 m^3 per m^3 of coal
   (sometimes up to 15 to 30 m^3) *

   Sand/gravel - 15-20 m^3/m^3
   Sand - 12-18
   Tails - 10-20

2. Electric power consumption

   Coal - 24.2-26.5 kw-hr/m^3
   Sand/gravel - 4.9- 6.62 kw-hr/m^3
   Sand - 3.2-3.6
   Tails - 21.4

3. Pipeline service life

   large fractions - 6-8 months
   fine fractions - 12-14 months

   The consumption of pipe by wear is 0.52-1.5 kg/m^3 **

4. For rock transport, the capital investment is 0.29 to 0.71 rubles/m^3. The cost of technological equipment amounts to 43% of this figure.

5. Bar graphs showing the distribution of costs at various hydrotransport installations are shown in two figures. Electric power runs from 18 to 55% and wages 35 to 42% of the total.

*Ed. Note: These high values probably apply to gravity flume transport in hydraulic coal mines.

**Ed. Note: Presumably weight of pipe used up per m^3 transported, averaged for whole industry.

II.1.1 Chapter 1

In general, Chapter 1 is very good in explaining the physical phenomena such as turbulence and the various flow regimes of slurry flow. However, this chapter in particular is flawed by incomplete explanation of the experiments and of the test conditions relating to the many graphical plots of experimental data. The graphs are small and difficult to read. These graphs synthesize a large amount of test data which were obviously costly and time consuming to generate. It is unfortunate that a better job was not done in making the data clear and understandable.

Chapter 1 contains several important statements which are summarized below:

1. The author emphasizes the role of the ratio of particle size to pipe diameter, an area of neglect in Western practice.

2. Heterogeneous slurries possess high frictional losses because the internal friction caused by particle collisions increases.

3. Particle shape has little influence at high velocities.

4. "Since theoretical determinations of critical velocity (or deposition velocity) at the current state of development of the theory of carrier streams is quite difficult, the primary method of determination of critical modes of motion of slurries has been the experimental method."

5. For coarser slurries, deposition velocity becomes essentially constant at concentrations by volume greater than 15%.

6. For fine slurries, critical velocity becomes constant at volumetric concentrations greater than 25%.

7. Fine slurries at high velocities do not give a uniform concentration distribution but show a higher localized concentration at the center of the pipe.

8. An interesting hypothesis is offered which suggests that a cubic lattice is less stable hydrodynamically than a tetrahedral lattice. The latter is apparently representative of a finely dispersed slurry.

The conclusion derived from Chapter 1 is that if the author had paid as much attention to graphical details as to the explanation of hydrotransport phenomena, this chapter would be an outstanding contribution to the literature on slurry pipelining. As it stands, a great deal of impact is unfortunately lost.

II.1.2 Chapter 2

Chapter 2 on slurry thickening or slurry de-watering is interesting in that several new types of de-watering devices are illustrated. These are: a) a differential trough which uses a horizontal slice into an open channel slurry stream, b) an inertial-gravitational thickener which may be thought of as an angled tee with a free backflow into the reducing branch, and c) a vibration de-watering device. These are described in good detail, with fairly explicit theory in some cases and graphs correlating variables. Unfortunately, only one specific case is illustrated showing the differential trough to be a respectable thickener but not an outstanding one. For example, 50% of a 0.15 x 0 mm. material was removed from a flow having a volumetric concentration of 34.4%.

In conclusion, Chapter 2 describes three new concepts for de-watering. They appear to be low-wearing components, yet have a good efficiency in thickening fairly coarse slurries.

II.1.3 Chapter 3

The introduction to Chapter 3 explains the mechanics of wear very well. Most important is the explanation of cavitation and its effects on wear. This phenomenon has been under-rated in Western practice as a cause of wear. To the writers' knowledge, the early part of this chapter represents the most detailed discussion in the literature of cavitation in slurry systems.

On the other hand, the treatment of corrosive wear is poor. However, the treatment of erosive wear is extensive. As noted before, graphs used to illustrate a point are confusing and difficult to follow. The tests from which the charts and graphs evolved are neither discussed in detail nor referenced.

Some of the highlights of Chapter 3 are:

1. Wear due to solids occurs differently in two flow regimes, by impact at low concentrations and high velocities, and by sliding friction at high concentrations and lower velocities. Erosive wear is proportional to velocity to the first power for a sliding bedload and proportional to velocity squared for full suspension wear.

2. Elbow wear is reasoned to be $(4.5\frac{l}{r}\frac{P_s}{P_m})$ times the wear in a horizontal pipe where l = arc length of the elbow, r = radius, P_s = solids density, and P_m = mixture density.

3. The exponent n in the wear-velocity relationship can increase to 3.0 for heavy abrasive materials at velocities more than two times the deposition velocity. Cavitation is thought to be influential on wear at higher velocities.

4. An interesting graph (Fig 29) is included which shows how solids concentration affects wear intensity; the wear rate is high until the saturation concentration is reached, at which point the wear intensity becomes constant. The saturation concentration varies with the solids type but is inversely proportional to particle size. The alloy Kh25N2 (presumably 25% chrome and 2% nickel) is shown to have superior wear resistance among the steels.

5. Without reference to the slurry or flow properties, a rating of relative wear is given for several pipe materials exposed to full suspension slurry flow. Rubber and ceramic are shown to be 4 times more wear resistant than low carbon steels. Basalt is shown as 60-100 times less wear resistant than steel. Thus the importance of elasticity is demonstrated for fully suspended particles which impact the surface at nearly 90°.

6. For sliding (friction) wear, corundum and hardened steels outperform rubber and unhardened steels.

7. Steels with high carbon and manganese content (martensite structure) have good wear resistance.

8. Because of the effect of gravity on solids velocity, wear in a vertical pipe is about twice as great for downflow as for upflow.

Severe pump wear has been recorded when pumping mine water with low levels of fine abrasive solids ($2\% < C < 8\%$). Pumps in direct series have been found to show increased wear in successive stages suggesting that increased pressure promotes increased wear. Strangely enough, with $C < 2\%$, pumps last longer than for clear water service. Above 2%, solids wear increases sharply.

If pipe relative wear is unity, impeller wear is 20 times, and casing wear is 75 times. Impeller wear is said to vary as the cube of the diameter and speed. As the exit angle of the impeller vanes increases, wear resistance increases. Wear rate decreases with increasing number of vanes. As solids concentration increases, vane wear decreases and flow increases. Generally, wear is directly proportional to particle size for solids concentration by volume up to 25%. Above that, specific gravity of the solids is more important than particle size.

Large diameter pumps wear better. Optimum specific speed is 60 to 80, but units are not specified.

Corundum coating and hardening are recommended for pipe protection. Medium carbon steel wears about 1.5 to 1.8 times longer than low carbon steel. The use of zonal high frequency induction hardening increases wear resistance by a factor of 2.2 to 2.5. Hardening increases the cost by 12% but service life is increased 2 1/2 fold. Corundum coating (52%) with epoxy resin (35%) and dibutyl pthalate (10%) give the best results.

Rubber linings increase pipe costs by 2.5 times but outlast metal pipes 15 to 20 times. Basalt increases pipe weight 2 1/2 times, cost by 30%.

Wear resistance of polyethylene pipe is 1/10 that of mild steel, yet its lightness can reduce labor costs substantially. New developments in pipe materials are being directed at basalt particles, granulated copper furnace slag, ceramic, etc. in a plastic binder. Porcelain appears to give the best wearing characteristics.

II.1.4 Chapter 4

Chapter 4 deals with reliability of Hydrotransport Installations, which is determined by stability of maintaining the transportation mode and durability of the equipment. Stability involves prevention of plugging by control of concentration and velocity. For gravity systems, air in the system is also important. Durability concerns wear, both corrosive and erosive.

Some idea of the extensive Russian hydrotransport experience is suggested in a table listing causes of failure of hydrotransport installations. Plugging of pipes constitutes 53% of the failures, 19% from loss of water, 20% from wear of the pipes. Failures can be classified as extended, as produced by wear, or sudden, as produced by power failures.

The mean time between failures can be increased if wear resistance and component dependability (non wear-related) are equalized.

Failures in a hydrotransport system develop in three periods:

1. break-in period - defective manufacturing and materials fail

2. normal operation

3. extended period - aging and wear of elements

The first and third periods have high rates of wear. Old parts should be replaced during the last period for maximum reliability.

Pumps as a whole, fail much faster (twice) than impellers. (e.g. 1007 hr for an impeller to 471 hr for a whole pump). The recommended approach is to increase operational reliability by attempting to balance the failure time of various pump components and to reduce the time required for repair. An entire slurry pump replacement should be accomplished in one 8-hr shift.

II.1.5 Chapter 5

In Chapter 5, types of measurements are discussed: Continuous or fully automated, and continual or remote sensing of limiting values. Regulation of solids and liquid feed must be accomplished with quick response.

Slurry density is measured conventionally by a nuclear density gauge or in special cases by measuring the draft of one of the floats of a floating slurry line, or the bending of a slurry pipeline section.

Flowrate is measured generally by an electromagnetic flowmeter. An extensive explanation is given for its operation but no schematics are shown. Similar treatment is given to combined measurements of flow and concentration to produce solids throughput.

One of the more interesting instruments described is the radioisotope densitometer (Cobalt 60) with a gamma container. The gauge rotates around the pipe in an Archimedes spiral with simultaneous advance along the axis of the pipe. Twenty-one revolutions are made around the pipe in 2 minutes. The Polish invention was described recently at Hydrotransport 4 in Banff, May, 1976.

II.1.6 Chapter 6

This chapter on Hydraulic Shocks is an excellent treatment of the operational techniques required to minimize pressure transients in slurry systems. The importance of air in a slurry in reducing the propagation velocity of the shock wave and the pressure of the shock is noted.

Careful start up of slurry pumps in series is emphasized. A fast start up of the second pump may initiate cavitation while a slow start up may induce plugging. One gets the impression that the Russian practice includes start up and shut down with a slurry rather than with clear water.

A brief but good discussion is presented on the pressure transients produced by high static lift pipelines. Because slurry pumps have larger passages than water pumps, they offer less resistance to back flow (3 to 8 in). Simultaneous shutdown of pumps in series (power failure) creates a large pressure transient. Start up and shut down operations are detailed to minimize hydraulic shock.

Shock dampeners used are of two types: a variable pressure limit dampener and a preset fixed pressure dampener. A mechanical dampener is discussed. Its disadvantage is that a shear pin must be replaced when the device opens to reduce the pressure transient. An air-hydraulic chamber with automatic refilling with air is also described.

The contribution of this chapter is mainly the well-written explanation of pressure transients. Equations are applied to everything, but little is done with them for design purposes.

II.1.7 Chapter 7

Chapter 7 deals with economic analysis of hydrotransport. The importance of wear is emphasized for gravity systems, as opposed to energy requirements for pumped systems. The main application here appears to be hydraulic stowing in a mine.

The strong effect of solids concentration on productivity or reduced specific energy cost is compared for pressurized and gravity slurry systems. As expected there is less influence on gravity flow systems, and as expected, the highest concentration attainable concomitant with operational stability is the optimum.

The economic analysis is generally comparable to that used in Western practice. The major contribution of this chapter is the comparison between pressurized flow and gravity flow for the optimum velocity of transport. For pressurized transport the economic velocity is 1.6 times the deposition velocity, for gravity flow, it is 2.5 times the deposition velocity. Based upon a case involving a 358 mm diameter pipe carrying solids of mean size 2.5 mm, the economic velocity zone is much more extensive for a gravity system than for a pressurized system.

The second major contribution of this chapter is a series of nomographs prepared for gravity flow (hydraulic stowing) from Polish practice. Had these nomographs not been so highly condensed and presented in such an unclear fashion, they probably would be a major contribution for design purposes. Similarly, a confusing plot of pipe protection methods loses its importance due to the manner in which it is presented. This chapter could have been outstanding for its wealth of material. As presented, though, the reader cannot extract very much of importance, except for some general ideas.

II.1.8 Conclusions Regarding the Pokrovskaya Book

This book covers a wide spectrum of slurry systems based on extensive Soviet experience, particularly in mining systems and hydraulic stowing systems using slurry pipelines. It includes excellent presentations of the subjects of cavitation, pumps, homogeneous slurry structure, erosive wear and operational techniques, much better than presently available in western literature.

The major criticisms of the book are:

The many equations presented are seldom used for design purposes or examples. The graphs and tables are not very useful for design purposes because of inadequate explanation and lack of clarity.

In conclusion, the book is a welcome addition to the world literature on slurry transport.

II.2 REVIEW OF BOOK BY V.V. TRAYNIS "PARAMETERS AND MODES OF HYDRAULIC TRANSPORT OF COAL BY PIPELINES" (1970)

II.2.0 Foreword

In 1968 there were 14 hydraulic mines and 4 hydraulic sections in operation in the USSR with a planned capacity of 14 million tons of coal per year. The three largest surface pipelines are 10 km each. The coal is used by electric power plants and a metallurgical plant. This fact serves to alert the reader to the vast Soviet experience in coarse coal slurry transport.

Four authors are cited for work in the direct combustion of coal. Two pilot plants burning 50% coal have been in operation in the USSR many years. However, in a later statement, Traynis states that hydraulic transportation of finely dispersed, highly concentrated coal suspensions suitable for direct combustion is an area which has remained completely unstudied.

Traynis states, "Calculations have shown that all the advantages of combustion of coal suspensions are most fully realized when it is combined with ----- hydraulic mining, beneficiation, and hydraulic transport."

II.2.1 Review of Chapter 1 from Traynis (from Part 1 - Lump & ROM Coal)

Chapter I deals with parameters of hydraulic transportation. A brief historical survey of headloss correlations is presented along with an emphasis on the relationship between flow regimes and particle size distributions. For example, it was discovered that critical (deposition) velocities of coal with fines increased with increasing concentration up to a limit, thereafter decreasing. Thus the viscous effect of fines in mixed slurries was revealed.

Numerous headloss equations are given and the point is made that short distance pipelines for coal mining did not require exact correlations. The author criticizes several of the correlations, particularly for their empiricism. The encouraging aspects of the test work examined were the large pipe diameters and long test loops used to obtain data. The discouraging aspect is the heavy reliance on empiricism in the data analysis despite what appears to be extensive pipeloop data.

The Newtonian characteristics of a fine coal slurry up to 20% volume concentration are noted. For higher concentrations and for coarse slurries, the same theoretical approach to the headloss equations as developed by the French 25 years ago, are adopted by the Russians with some modifications to handle particle size and distribution more realistically. The importance of particle size and distribution are emphasized. Weighted mean drag coefficient is adopted to represent the effect of the various size fractions. Where fines become excessive, the properties of the heavy medium carrier replace those of the clear water carrier.

II.2.1.1 Wheel Stand

A potentially outstanding contribution to slurry pipeline technology is revealed in this chapter. It is the wheel stand developed by Traynis and Rukov in 1966 at the Skochinskiy Institute (based upon an earlier English idea by Worster and Denny, see Ref. 15). Pipe of diameter D is bent into a wheel of diameter D_k. Slurry is poured into the wheel, filling it to not more than 1/3 of its capacity (Worster & Denny filled their wheel 3/4 full). The slurry slides relative to the moving walls of the rotating wheel, just the opposite of actual pipeline flow but behaving hydrodynamically like the latter. Three wheel stands of 0.1 m diameter glass pipe, 0.2 and 0.3 m steel pipe were constructed with diameters of 1, 2.6, and 5_m respectively. Performance equations are presented by the author. Power consumption was measured by dynamometers. Circularity of the wheel and wheel balancing are important. Overfilling the wheel beyond 1/3 capacity places solids in the ascending portion of the pipe where gravity distributes the concentration of solids uniformly and reduces its effect on wall contact. Visual and cinematic observations confirmed flow behavior similar to pipe flow even to the point of critical (deposition) velocity. Dynamometer readings and changing noise levels indicate critical velocity much like pipeline flow.

As nearly as can be determined, the wheel stand provides most of the data a pipe loop test offers, but on a much smaller scale, namely: power consumption, solids degradation, erosive pipe wear, and deposition velocity (but probably not corrosive wear). Sufficient evidence is given for rock and coal of various sizes to confirm the correlation of wheel stand results with pipe loop test data for horizontal pipes.

The author summarizes the chapter with a comparison of his headloss equations with four other researchers. His is superior as might be expected, otherwise the comparison would not have been made. The author's correlations excell in 3 of 5 categories producing predictions within 5% of the experimental values. Considering the amount of empiricism involved and the lack of details on various experiments, the Traynis headloss and deposition velocity correlations cannot be unequivocally accepted.

II.2.2 Chapter II - Degradation of Coal

Chapter II deals with degradation of coal during hydrotransport. Traynis properly commences this chapter on an economic note stating that 6x0 mm coal commands about 1/3 the price of 100 + mm coal. In addition, he notes that beneficiation of fine coal costs four times more in capital investment and five times more in operating expense than coarse coal, whereas dewatering costs of fine coal are ten times those of coarse coal.

Coal degradation was studied in a 0.2 m wheel stand (600 tests). It showed conclusively that pipeline wear is much less than repeated passages of solids through a centrifugal pump as in a recirculating pipe loop test.

This chapter deals with a subject about which little is known in Western practice. Only a handful of references exist in the literature describing in all cases rather limited information on coal degradation from hydraulic transport.

Some of the highlights of this chapter are:

1. Velocity of flow (up to 6 m/s) does not degrade fine coal (0-0.063 mm) but does degrade coarser fractions (to 6 mm). The latter, called lump coal, moves along the invert of the pipe and is subjected to degradation by its contact with other large particles and the pipe wall. The fine coal rides in suspension and is not exposed as much to the forces of degradation.

2. The coefficient of friction for anthracite against steel is about 0.26 for a velocity range of 0.7 to 3.1 m/s.

3. Degradation of coarse coal during pipeline transport is practically independent of the concentration of coal up to 33% by volume.

4. Degradation of coarse coal is independent of pipe diameter.

5. Degradation of coal depends little on the initial size of lump coal. This is explained again by the saltation and sliding bedload flow regimes, characteristic of lump coal.

NOTE: In this chapter many references are made to tests with pipe lengths up to 1000 km, yet it is seldom clarified when an actual pipeline was used and when the wheel stand was used to simulate a long pipeline. This is particularly true for the 50 km distance often referred to.

6. A simulated mis-matched pipe joint of 1.5 mm in the invert of the pipe increases the degradation of coal only in the lump size which travels along the bottom of the pipe.

7. Reduced energy requirements for pipeline transport are achieved only when coal is ground to below 1-3 mm.

8. Freshly ground coal will degrade about double that of rounded coal.

9. The smaller the coal, the more resistance it has to crushing.

10. The degradation of coal occurs primarily in the first 10 to 20 km of pipeline and is proportional to the amount of ash in the coal. A higher ash content causes increased degradation as well as producing it over a longer length of pipeline.

11. Pipes are ground smooth by run-of-mine coal in 3-4 weeks, requiring tens of thousands of tons of coal.

12. Comminution theory is presented with a series of experimental form equations including the Rosin-Rammler equation. Numerous assumptions are made and verified by pipeline and wheel stand experiments with coal. The degradation of coal by pipeline transport is represented by two equations depending on whether knowledge of reductions in all size fractions is desired or whether just the reduction of one screen size is wanted.

13. The wheel stand can be used to measure the degradation of coal from pipeline transportation. The same slurry speeds and values of coal concentration assumed for future pipelines need not be used because these parameters do not strongly influence the crushing of coal.

14. Interestingly, the comminution theory is extended by replacing the pipeline length or particle size dependency by electric power consumption. A mathematical model with several coefficients is examined and evaluated for coal properties (strength, ash, and wettability of gangue material).

Despite the extensive experimental and analytical work by the Russians on the degradation of pipelined coal, it is encouraging to note that the actual degradation is not very significant, except for large lump sizes at distances over 10 km or when fine coal is passed more than 10 or 15 times through a centrifugal pump.

II.2.3 Chapter III - Wear in Pipes

The chapter begins with a literature survey showing the earlier confusion among Russian researchers as to the variables affecting pipe wear. Reference is made to the 0.2 m pipe diameter wheel stand containing a 189 cm^2 copper wear insert. The author presents a rather confusing array of variables for describing wear: absolute wear, specific wear, averaged specific and absolute wear, and throughput capacity. Throughput capacity is expressed in thousands of tons of solids transported per 1 mm of wear of the invert of the pipe.

Erosive wear by coal was shown to be small so most of the wear stand tests were made with rock.

The throughput capacity for anthracite (0 to 50 mm) increases from 30,000 tons/mm at 30 km to 122,000 tons/mm at 400 km, an increase of 3.5 fold due to the crushing and rounding of the anthracite.

Removal of ash in coal is most significant. Reducing the ash from 24% to 8% in anthracite permits an increase in throughput capacity (or decrease in bottom pipewear) of 4-fold. For another coal, reducing the ash content from 16% to 8% increased the throughput capacity seven times over a distance of 50 km. These tests involved coal sizes of 50x0 mm. For 3x0 mm coal, the slight wear of the copper plate was immeasurable.

Wear is shown to be almost directly proportional to velocity and the specific gravity of the slurry for the sliding bedload regime.

Wear increases rapidly as particle size increases from 0x1/2 mm to 1x6 mm. Then the wear decreases significantly for larger particles because the flow regimes change.

Rounded quartz solids will increase the wearability of a pipe almost three-fold over that of freshly crushed solids.

A theory is described to predict at what distance along the pipe a slurry produces maximum pipe wear. This is explained physically by the intensive rupture of solid particles at their weakest points forming new surfaces with sharp corners and edges. With further transport the corners become rounded. For coal the maximum wear of a pipe was found to be between 5 and 10 km.

Hardness of the solids influences the wear of the invert of the pipe only in the sliding bedload regime. The addition of clay to a slurry reduces pipewear not because a heavy medium is produced to keep some of the larger solids in suspension, but apparently because the clay lubricates the solids and the pipe invert.

The Russians maintain that for coal particle sizes greater than 3 mm, the hydraulic drag (headloss) remains constant.

In conclusion, if the wheel stand duplicates actual pipe wear and solids degradation as Traynis claims, then the extensive tests made with the wheel stand have contributed substantially to the understanding of pipe wear and solids degradation.

II.2.4 Part II, Chap IV - Fine, High Concentration Coal Suspensions

The rheology of coal slurries is discussed in detail in this chapter. Traynis justifies the importance of fine coal slurries by the possibility of pumping them directly to a furnace for combustion. The moisture content of the slurry reduces the efficiency of combustion because 800 kcal of energy are required to evaporate 1 kg of water.

Thus, 3 to 10% of the coal is required to evaporate the water in the slurry but this is offset by the savings in dewatering costs. Traynis states that a complete hydraulic system of hydraulic mining, pipeline transportation and direct combustion of the slurry will reduce power generating costs by 20 to 30%. The recommended particle size should be less than 0.2 mm (65 mesh) with the majority of sizes in the 0.05 to 0.1 mm (70 to 150 mesh) range.

The Russian approach to rheology is fairly similar to Western practice but with a few modifications, primarily in terminology. Coal slurries which produce pseudoplastic flow models are called liquid dispersed systems, while yield-pseudoplastic flowmodels are called solid dispersed systems. A static yield stress is differentiated from a dynamic yield stress, the latter being about 33% higher than the former.

Several Russian viscometers are mentioned, but not in detail. A discussion suggests that slurry rheology properties are a function of the various viscometers. A pipeloop test system utilizing 10 different pipe diameters up to 205 mm was used to compare pipeline flow data with viscosity measurements. Four flow regimes are described with the middle two being of practical significance. Reynolds numbers are defined for the flow regimes, and headloss equations, although slightly empirical in design, are specified.

A very good discussion is presented on the structure of fine coal suspensions with attempts made to define the existence of a yield point, lack of thixotropy, and coagulation structure. Traynis is quick to emphasize that coal suspensions of identical concentration and size distribution can give quite different rheological properties because of the constituents of the coal. Therefore, rheology measurements are necessary for studying fine, high concentration slurries.

The roles of particle surface area and solids concentration are discussed in detail, suggesting that there is a limiting concentration above which the slurry viscosity and yield stress increase rapidly. For coal, the volumetric concentration is said to be 20 to 30%.

The beneficial use of additives and ultrasonics on the reduction of viscosity of the slurry is mentioned briefly.

Traynis states that prediction accuracy of headloss from rheology data range from 15 to 18% but does not indicate the direction of the variation. Russian practice is similar to Western practice in that the flow regimes are identified, then friction factors are calculated according to the Reynolds number relationship for each flow regime.

A distracting feature of this chapter is the insinuation that Russians discovered numerous hydraulic phenomena much earlier than commonly acclaimed in Western literature. Four times, Traynis lists Russian researchers, whose works precede those of non-Russians generally acknowledged as the discoverers of certain hydraulic phenomena.

II.2.5 Chapter V - Properties of Coal Suspensions

This chapter takes a theoretical approach to the rheology of fine coal suspensions, particularly for the low velocity (low shear rate) deformation as a function of the suspension properties. The practical application is related to slurry plugging at low velocities, slurry pump start up and slurry flow after a pump failure in a booster station.

The experimental work is done with several rotational viscometers, none of which is described in detail. The shear rates studied are very low, much lower than those studied in Western practice, at least to this writer's knowledge. Considerable detail is given to categorization of low speed flow regimes, elastic, plastic, viscous, and creep phenomena. The structural formation of coal suspensions is due to the presence of mycelia --- threadlike formations of a resinous substance. Except for very low shearing rates, this structure is quickly broken down. It is of importance at very low speeds, as for start up of flow.

A mechanical model is devised to explain the stress-deformation relationship. It is a complex model consisting of Hookean, Kelvin and Schwedov-Bingham bodies.

This chapter is impressive in showing how a complicated phenomena can be described mathematically with the aid of experimental data and applied to the determination of headlosses for slow flows and for transient pressures in slurry flow in pipes. The writer is not aware of any comparable work in Western practice. One might argue perhaps, that the class of problems which can be solved with this mechanical model is not a major one and not very significant.

II.2.6 Chapter VI - Lump Coal in Coal Suspensions

The preceding chapters lead ultimately to a favorite subject of Traynis, the use of a heavy medium of fine coal to transport lump coal. The governing criterion is stability of the slurry. That is, when flow stops, the lump coal stays in suspension and does not deposit on the pipe invert. Traynis is seeking the optimum size distribution for a coal slurry, one that is cheap to grind, to transport, to dewater if necessary, or to utilize directly for combustion.

Three sets of experiments were made with various coal suspensions in a 104, 120, and 152-mm diameter pipe transporting anthracite lumps up to 25 mm in size. Rheological measurements were made on the five suspensions. Specific energy curves were developed from the headloss data to show the advantages of using a heavy medium. The optimum fine coal slurry density was about 1.12 g/cc. The energy requirements for pipeline transportation were less than hydrotransport of the same lump coal in water, even considering recycling of the carrier suspensions by a return pipeline. Total maximum coal concentration by weight approached 50% in some of the tests. The fine coal must have a concentration sufficient to just produce a yield point and weak plastic properties.

Traynis points out that for the direct combustion of coal slurry, the concentration of the carrier suspension is necessarily high to reduce the moisture content. Then the plastic properties require more energy for transportation by pipeline.

Transportation costs can be reduced by addition of a stabilizing reagent, SSB (composition not given). Pipeline length must exceed 50 km to offset the cost of the additive. Headlosses are reduced because the additive breaks down the plastic structure of the coal slurry at medium velocities. However, the slurry cannot be stored without agitation because the solids form a dense deposition.

This chapter is neatly concluded with a brief discussion of the importance of a systems approach to mining, hydrotransport, and product end use.

II.3 REVIEW OF CHAPTER 4 BY NUROK (1970)

This Chapter is entitled, "Calculations of Hydrotransport of Useful Minerals and Waste Rock".

In the Foreword of this book, it is stated that V. V. Traynis wrote Sections 1-9 (pp. 60-103 in the translation) of Chapter 4. This part of the chapter is essentially a summary of some of the more extensive material covered in the Traynis book which was published the same year, 1970. There is some additional material such as Figure 23 which gives headloss data for highly concentrated coal slurries. Also included is Figure 25 which plots friction factor against Reynolds number. The latter part of Chapter 4 deals with coal pumps and slurry pumps. Figure 35 shows what is probably the entire range of Russian slurry pumps in terms of head-flow-rpm characteristics. Some of the highlights of this chapter are:

1. The largest slurry pump for sand and gravel appears to deliver 3340 liters/sec or 118 cfs at 100 psi at 300 rpm with an efficiency of 72%. Efficiencies generally range from 63% to 73% with the larger pumps having the greatest efficiencies. This pump appears to be a dredge pump with an unbelievable 5082 hp requirement at maximum power.

2. Technical characteristics are given in Table 17 for slurry pumps and in Table 18 for coal pumps. The latter table lists the largest pump at 20 cfs at 639 psi! Horsepower rating is 5028 hp at 65% efficiency and 1450 rpm! With motor and baseplate, total weight is 67 metric tonnes! This pump is a two-stage centrifugal pump.

Western practice is just beginning to develop this kind of slurry pump, although not specifically designed for coal. The efficiencies are lower for the coal pumps because they are intended to handle coarser particle size and therefore, must have larger clearances within the impellers.

3. Table 19 lists the quantity of solid material (slurry properties unlisted) in thousands of cubic meters delivered by the pump before complete wear of various parts. Three pump types are listed: slurry, mud and coal pumps.

4. Table 20 is of limited value because the various types of abrasive slurries are not defined.

5. Table 21 lists the mean service life of slurry pump parts for water pumping only.

6. The coal pumps experience higher wear than slurry and mud pumps because greater heads are required for vertical hoisting. Hence, the higher impeller speeds impart more kinetic energy to the coal lumps leading to greater wear.

7. Several equations are quoted for pipe wear. They are either very simplified or too complex, with considerable empiricism.

8. A steel pipe with a corundum coating is mentioned, something which is not available in Western practice as a slurry pipe. Also mentioned is that basalt inserts extend wear life three-to-four-fold and rubber linings increase wear life 10 times or more.

9. The chapter includes data on gravity flow in open flumes.

In conclusion, Nurok's Chapter 4 is most valuable for its treatment of centrifugal pumps applied to hydrotransport. The latter part of Chapter 4 deals with coal pumps and slurry pumps. Figure 35 shows what is probably the entire range of Russian slurry pumps in terms of head-flow-rpm characteristics.

II.4 GENERAL COMMENTS

Three volumes have been reviewed concerning the hydrotransport of coal, primarily coarse coal. The first by V. V. Traynis in 1970 deals directly with coal. The second by V. N. Pokrovskaya in 1972 deals with means of increasing the effectiveness of hydrotransport. The third is a chapter written by Traynis in a general hydraulic mining handbook edited by Nurok. Traynis writes as a practitioner rather than a theoretician. Pokrovskaya deals ostensibly with very practical subjects but manages to theorize on them extensively. Traynis's chapter in Nurok's book is a summary of his 1970 book with some additional material.

Traynis's book deals with headloss theories, a description of the wheel stand, several aspects on coal degradation, erosive wear, and the rheology of fine coal suspensions. Pokrovskaya's book covers in a pedantic manner, flow regimes, dewatering, erosive wear, operation and maintenance, instrumentation, and economics. Traynis's part of Chapter 4 in Nurok's book is a synthesis of his 1970 book. The chapter also includes an extensive section on pumps.

All three volumes stress a systems approach which suggests a well-balanced background of the authors. Since two of these books (Traynis's and Nurok's) were published in 1970, it is obvious that the Russians are leaders in coal hydrotransport theory and practice from the mine to the washing plant. "Russia", in this case includes Polish practice which apparently plays a significant role. It is also apparent that Soviet insight into the structure of fine coal slurries is of the highest order even though they don't have an existing long distance pipeline comparable to the Black Mesa coal slurry pipeline in the U. S.

When one considers the circumstances behind Soviet coal mining (wet mines, steeply pitched seams) it is obvious that their leadership stems from the logical way to develop their coal mines hydraulically. This in turn encourages hydraulic hoisting to the wash plant. This requires robust, high-pressure pumps capable of passing large solids. With this familiarity and hydraulic background, long distance pipelines will become the next logical step along with direct combustion of the slurry.

All three volumes are well written and well translated. Explanations of physical phenomena are explicit and well planned. Probably the two most conspicuous shortcomings are the absence of raw data and the economy of structure of the graphs. However, text books normally do not contain raw data and these are no exception. However, many postulations are made and substantiated with graphical data, but since Westerners have virtually no access to the basic references, a certain amount of creditability is lost for Western acceptance. If for no other reason though, the postulations will serve as a helpful guide in Western research on the hydrotransport of coal slurries.

Whether it was an economical decision by the publisher or a national pedantic technique, all three volumes display graphs containing a tremendous amount of data condensed into numerous confusing curves. Their complexity is compounded further by the very small physical size of the graphs. Most graphs are less than 4 square inches and extremely difficult to read. One can almost sense the translator's frustrations in deciphering titles and units on the graphs.

Minor complaints are the difference between Russian and Western nomenclature, a few instances of misunderstood technical jargon, and an occasional tendency by the authors to point out that certain technological discoveries were made by Russians at an earlier date than non-Russians to whom credit is usually given.

The outstanding contributions are the explanations of the flow regimes by Pokrovskaya, the experiments with heavy media by Traynis and his development of the wheelstand, and the section on centrifugal coal pumps in Nurok's book.

While there can be no perfect book on slurry pipelining because of its wide application and complexity, there are specialty books on slurry pipelining in Western literature. However, none can compare with these three volumes on hydrotransport. As Traynis emphasizes, the differences in coal properties strongly affect the hydraulic characteristics. This reviewer (Faddick) has found this to be true in his own experiences. Therefore, while the Russian books will not provide ready answers, they at least will suggest proven techniques to find the answers.

III. COMPARISON OF TEST DATA AND CORRELATIONS

III.1 GENERAL

Only a small amount of data on coal hydrotransport is included in the 1972 book by Pokrovskaya (Ref.10) which is devoted primarily to hydrotransport of sand, minerals, etc. Therefore, most of the review effort to evaluate test data was devoted to the 1970 book by V. V. Traynis (Ref.9) entitled, "Parameters and Modes of Hydraulic Transport of Coal by Pipelines" and to the Chapter 4 entitled, "Calculations of Hydrotransport of Useful Minerals and Waste Rock" from the 1970 book by G. A. Nurok entitled, "Hydromechanization of Opencast Workings" (Ref.11). This chapter includes a section written by Traynis, which is essentially a summary of his complete book.

III.2 PRESSURE DROP AND CRITICAL VELOCITY FOR HORIZONTAL PIPES

The book by V. V. Traynis (Ref.9) contains his recommended correlations for pressure drop and critical velocity for hydrotransport of lump coal and run-of-mine (ROM) coal in horizontal pipes. A summary of Traynis' data and recommendations is included below, using symbols which are generally accepted in the English literature (e.g. Govier and Aziz, Ref.12).

When a homogeneous slurry of small particles moves through a horizontal pipe, the head loss is expressed by the equation

$$i = i_o(\rho_m/\rho_o)$$

where ρ_m = density of mixture

ρ_o = density of water (1)

i_o = head loss per unit length of pipe for water

This equation is applicable to fine coal (less than 1 to 1.5mm) slurries at solid concentration (C_s) up to 15 to 20% by volume where the viscosity of the slurry is assumed to be identical to that of water and there is no slip between the particles and the liquid. (It also applies to sand slurries with sizes less than 0.1 to 0.2mm).

When particles have appreciable size and a density greater than that of the suspending medium the head loss has an additional term Δi due to interaction of the solid particles with the liquid or suspending medium:

$$i = i_o(\rho_m / \rho_o) + \Delta i \qquad (2)$$

The additional head losses are a function of the parameters

V_m = average slurry velocity

D = pipe diameter

g = gravitational acceleration

ρ_m = density of mixture (slurry)

ρ_o = density of water

ρ_s = density of solid

d = particle diameter

V_o = terminal settling velocity of a particle

By dimensional analysis, the following functions are selected:

$$\Delta i = \frac{\Delta P}{L\rho_o g} = f\left[\frac{\sqrt{gD}}{V_m} \cdot \frac{\rho_m - \rho_o}{\rho_o} : \frac{V_o^2}{gd} \cdot \frac{\rho_o}{\rho_s - \rho_o}\right] \qquad (3)$$

Where Δp is pressure drop and L is length

By equating the particle weight to the drag on a falling sphere in water

$$\frac{\pi d^3}{6}(\rho s - \rho o)g = C_D \frac{\rho o V o^2}{2} \frac{\pi d^2}{4} \qquad (4)$$

or

$$C_D = \frac{4}{3} \frac{gd}{V_o^2} \left[\frac{\rho_s - \rho_o}{\rho_o}\right] \qquad (5)$$

where C_D = drag coefficient

Traynis introduces a drag factor

$$\psi = \frac{\pi}{8} C_D = \frac{\pi}{6} \frac{gd}{V_o^2} \left(\frac{\rho_s - \rho_o}{\rho_o}\right) \qquad (6)$$

He assumes the function in Eq. 3 is linear, and adds the term $\pi/6$ to the right side of Eq. 3 which becomes:

$$\Delta i = \frac{\sqrt{gD}}{V_m \psi} \left(\frac{\rho_m - \rho_o}{\rho_o}\right) \qquad (7)$$

He then introduces an empirical constant k, to take account of the flow of liquid around the solid particles, so the head loss equation becomes

$$i = i_o \frac{\rho_m}{\rho_o} + \frac{\sqrt{gD} \quad (\rho_m - \rho_o)}{k V_m \psi \rho_o} \qquad (8)$$

For coal lumps larger than 3 to 6mm (the higher value for coal of lower density) and rock lumps larger than 1.6 to 2mm, when the flow of the liquid around the solid is turbulent, the values of terminal velocity V_o in Eq. 6 are determined from the Rittenger equation with coefficients (a) determined by Richards:

$$V_o = a \sqrt{d(\rho_s - \rho_o)} \qquad (9)$$

where for quartz of density 2.65: a = 29

for coal of density 1.3: a = 26-29

Comparing this equation with Eq. 6, it is found that for coal and rock of the above grain sizes, the drag factors ψ are constant:

For quartz, waste rock, gravel and other rock:

$\psi = 0.6$

For coal (ρ_s = 1.3) $\psi = 0.73$

For anthracite (ρ = 1.65) $\psi = 0.65$

These values correspond to the equation

$$\psi \doteq 0.65 \left[\frac{0.66}{\rho_s - 1} \right]^{0.2} \qquad (10)$$

Traynis defines lump materials as particle sizes such that ψ is a constant. Lump coal is larger than 3mm and lump rock is larger than 2mm in diameter.

The drag factor ψ for anthracite is shown in Figure 1 and is seen to increase rapidly for sizes less than 2mm.

The critical velocity V_{cr} is defined as the mean velocity V_m at which the head loss equation 8 has a minimum (it therefore corresponds to Govier and Aziz' velocity V_m2, the velocity below which solids form a deposit on the bottom of the pipe, p. 642 of Ref. 12).

Introducing the Darcy-Weisbach equation:

$$i_o = \frac{\lambda_o V_m^2}{2Dg} \qquad (11)$$

where $\lambda_o = 4f$ (f = Fanning friction factor) and ignoring the variation of λ_o with Reynolds number $(DV\rho/\mu)$, Traynis gets:

$$V_{cr} = \sqrt{gD} \left[\frac{\rho_m - \rho_o}{k\psi \lambda_o \rho_m} \right]^{1/3} \qquad (12)$$

For run-of-mine coal, a mixture of lump classes greater than 3 to 6mm with finer classes, a weighted value of ψ_{cr} should be used which considers the presence of fine classes. This value will be greater than for lump coal (Figure 1).

Since calculation of ψ_{cr} is difficult, he introduces the parameter $c < 1$ to the second term of equation 8 and the equation 12.

Then for run-of-mine coal and rock mixtures:

$$i = i_o \frac{\rho_m}{\rho_o} + c \left[\frac{\sqrt{gD} (\rho_m - \rho_o)}{k\psi V_m \rho_o} \right] \qquad (13)$$

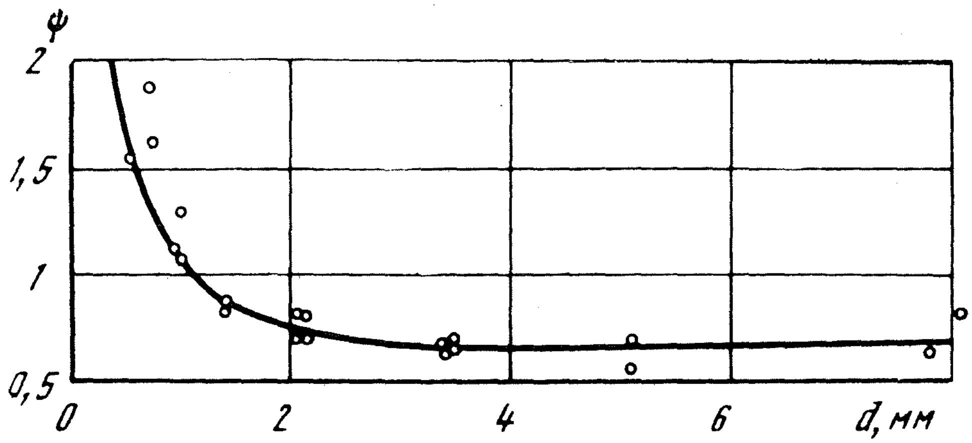


Fig. 1. Variation of Drag Factor ψ for free Fall of Anthracite Particles in Water

and

$$V_{cr} = \sqrt{gD} \left[\frac{(\rho_m - \rho_o)\ c}{k\psi\ \lambda_o\ \rho_m} \right]^{1/3} \qquad (14)$$

It follows that the factor c can be approximated by

$c = R_{+3}$ for coal (R_{+2} for rock)

where R_{+3} = fraction of coal greater than 3mm in size

(or rock greater than 2mm)

because this is equivalent to a slurry consisting only of lumps larger than 3mm in water.

Traynis analyzed the Russian experimental data from several sources (Figure 2) and concluded that:

$k \simeq 1.9$

and that a correction factor should be introduced for c

$c = 0.75\ R_{+3} = 0.75(1-R_{0-3})$

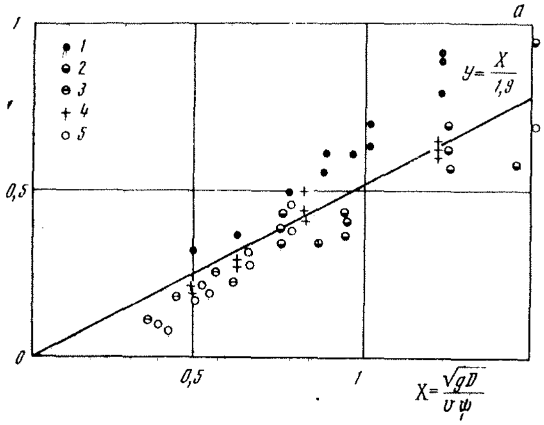
where R_{0-3} is the fractional content of coal below 3mm.

Also for rock:

$c = 0.75\ R_{+2} = 0.75(1 - R_{0-2})$

Experimental data are plotted in Figure 3A and 3B.

$y = (i - i_o \gamma_m)/(\gamma_m - \gamma_o)$ *



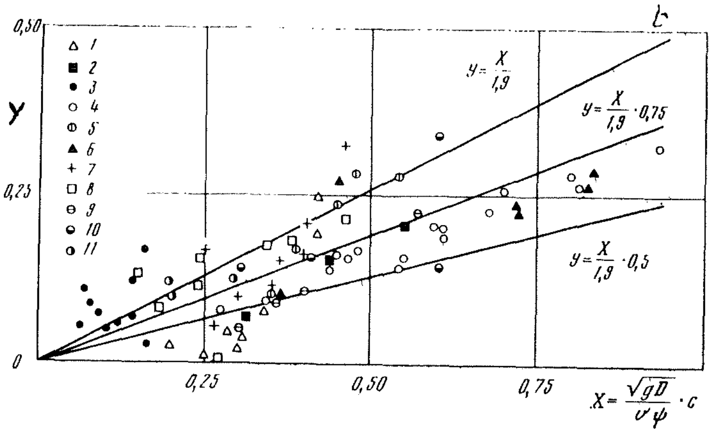
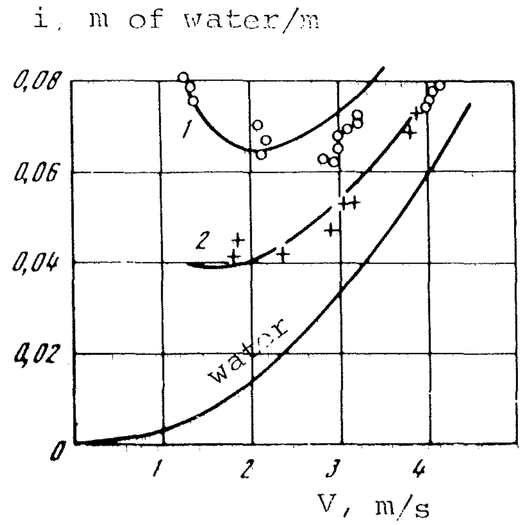


Figure 2. Agreement of Formulas (I.15) and (I.18) with Experimental Data for Hydrotransport of Lump (a) and Run-of-Mine (b) Coal: a, Calculated by Formula (I.15): 1, d = 6-13; D = 0.104; ρ_m = 1.048; 2, d = 6-50; D = 0.152; ρ_m = 1079; 3, d = 3-15; D = 0.152; ρ_m = 1070; 4, d = 70; D = 0.3; ρ_m = 1040, 1080, 1120; 5, d = 6-10; D = 0.2; ρ_m = 1095, 1041; Experimental Data: 1-3, By the Author; 4, R. Worcester (England); 5, R. Zahaczwsky (Poland); b, Calculated by Formula (I.18): 1, d = 0-25, D = = 0.152; ρ_m = 1100, 1120; R_{+3} = 50%; 2, d = 0-50; D = 0.2; ρ_m = 1099; R_{+3} = 50%; 3, d = 0-6; D = 0.2; ρ_m = 1100, 1240; R_{+3} = 15%; 4, d = 0-120; D = 0.409; ρ_m = 1100, 1140; R_{+3} = 60%; 5, d = 0-120; D = 0.357; ρ_m = 1100; R_{+3} = 60%; 6, d = 0-50; D = 0.357; ρ_m = = 1100; R_{+3} = 50%; 7, d = 0-15; D = 0.409; ρ_m = 1090, 1150; R_{+3} = 25%; 8, d = 0-15; D = 0.357; ρ_m = 0.357 ρ_m = 1040, 1100; R_{+3} = 25% 9, d = 0-120; D = 0.357; ρ_m = 1100; R_{+3} = 50%; 10, d = 0-70; D = 0.255; ρ_m = = 1065, 1160; R_{+3} = 50%; 11, d = 0.13; D = 0.202; ρ_m = 1060, 1130; R_{+3} - 28%; Experimental Data: 1, 2, Of the Author; 3, 10, Of N.A. Silin; 4, 5, 7, 8, 9, Of A. Ye. Smoldyrev; 6, Of Kondo-Mikhaylov; 11, Of N. Ye Ofengenden (d, mm; D, m; ρ_m, kg/m^3)

* Ed. Note: γ_m is the specific gravity of slurry.
γ_o is the specific gravity of water.



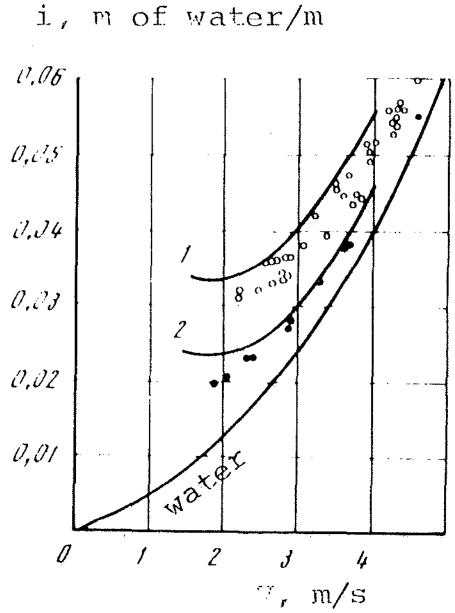


Figure 3A Experimental Points and Calculated Function i = f(v) for Hydrotransport of Run-of-Mine Coal d = 0-50 mm in a Pipe with D = 0.2 m (Experiments of the Author). R_{+3} = 70% (c = 0.5); 1, ρ_m = 1160 kg/m^3; 2, ρ_m = 1080 kg/m^3

Figure 3B Experimental Points and Calculated Equations for Hydrotransport of Anthracite d = 0-15 mm (R_{+3} = 40-30%) through a Pipe with D = 0.357 m (Experiments of A. Ye. Smoldyrev); 1, ρ_m = 1100 kg/m^3; 2, ρ_m = 1040 kg/m^3

III.3 COMPARISON OF DATA

The test data by Traynis (his Figure 3) were compared with experimental data reported by Weber (Ref.13) and with the theoretical predictions by Gaessler in the paper by Prettin and Gaessler (Ref.14) which were presented at the Hydrotransport 4 Conference. The data selected are for bituminous coal with pipe diameter of 200mm (7.9 in.) for both Traynis and Gaessler and 208mm (8.2 in.) for Weber. The data points selected are for volume concentrations of coal of 14.3 to 16%. The data are compared in Table 1.

A comparison of these data indicate the following tentative conclusions:

1. Traynis' equation for critical velocity as plotted in Figure 3 indicates a value of critical velocity of 1.6 m/sec which is only 84% of the value calculated by Gaessler and only 59% of the experimental value by Weber. Similarly, the head loss for pure water at this point is only 0.01 which is 62% of Gaessler's value and 50% of Weber's. This may be accounted for by the following:

Traynis states on his page 39 that in determining "the critical velocity, corresponding to the minimum head loss, a reserve factor of 1.2 was taken into consideration. This resulted from the fact that in most experiments, no minima were produced, apparently due to the danger of plugging of the experimental pipes." This implies that in Curve 2 of Figure 3, the critical velocity was only about 1/1.2 times the lowest test point at 1.8 m/sec. Inspection of his test points, however, might better by interpreted to place the critical velocity near 2.0 to 2.3 m/sec and $i_o = 0.016$ to 0.02, which is closer to the values reported by Weber and calculated by Gaessler.

However, the critical head loss calculated by Gaessler of 0.07 appears definitely higher than the experimental values of Traynis (0.04) and of Weber (0.035). This indicates that Gaessler's head loss calculation may be too conservative by a factor of nearly two.

A similar comparison of Traynis' and Gaessler's data is shown in Table 2 for a higher concentration of 30%. Again it is seen that Traynis' equation gives a critical velocity lower than observed by inspection of his own test data in Curve 1 of Figure 3 and also lower than predicted by Gaessler. However, the head loss calculated by Gaessler at the critical velocity appears too high by a factor near two.

TABLE 1

Comparison of Critical Velocity and Head Loss Data for Concentration C_s of 14 to 16% in 200 mm Pipes

Investigator	Traynis	Prettin & Gaessler	Weber
Source	Ref.9, Fig. 3	Ref.14, Fig. 6	Ref.3 Fig.7 & 11
ρ_s, Density of coal, gm/cc	1.52 (assumed)	1.522	1.53
C_s, Volume concentration	0.16	0.16	0.143
ρ_m, Slurry density, gm/cc	1.08	1.08	1.076
Grain size range	0-50mm	0-60mm	0-60mm
Mean particle dia.	?	10.0mm	12.7mm
Lump coal fraction	R_{+3} = 0.70	R_{+4} = 0.31 R_{+1} = 0.61 R_{+3} = 0.41	?
V_{cr} = Critical velocity m/sec.	1.6	1.9 (calculated)	2.7
Head losses at critical velocity:			
i_o (water)	0.01	0.016	0.02
i (slurry)	0.04	0.07	0.035
Head losses at V_m = 2.0 m/sec.			
(water)	0.015	0.017	0.0125
(slurry)	0.04	0.07	0.036

TABLE 2

Comparison of Critical Velocity and Head Loss Data for Concentration C_s of 30% in 200 mm Pipes

Investigator	Traynis	Prettin & Gaessler
Source	Ref.9, Fig. 3	Ref.14, Fig. 6
ρ_m Slurry density, gm/cc	1.16	1.156
Grain size range	0-50mm	0-60mm
Lump coal fraction	$R_{+3} = 0.70$	$R_{+3} \simeq 0.41$
V_{cr}, Critical velocity, m/sec.	2.1 (Equation) 2.5 (by inspection of Fig.3)	2.5
Head losses at critical velocity		
i_o (water)	0.023	0.03
i (slurry)	0.065	0.14

Unfortunately, Prettin and Gaessler did not report specific experimental pressure drop data for run-of-mine coal. However, from their Table 2 for the Gneisenau horizontal pipeline (1300 m long with 196 mm diameter) it may be concluded that, at the average transport velocity of 4.8 m/sec and the average solid content of 2 KN/m^3 (0-60mm coal), the average volume concentration of coal (ρ_s = 14.5) is

$$C_s = 2/14.5 = 13.8\%$$

The total flowrate is

$$Q = VA = 4.8 \frac{\pi}{4} (0.196^2) (60) = 8.68 \ m^3/min$$

Therefore, it is assumed that the two **pumps** are operating in series at a maximum head of 5.5 bars each. The head loss per foot is

$$i = \frac{\Delta p}{\rho_o L} = \frac{2(5.5)\ (10)}{1300} = 0.0845 \text{ m of water per m}$$

The corresponding Froude number is

$$Fr = \frac{4.8}{\sqrt{9.8(0.196)}} = \frac{4.8}{1.385} = 3.47$$

However, at Fr = 3.47 and C_s = 0.138, Gaessler's curves in Figure 6 predict a pressure drop of 12 m bar/m or 0.12 m of water per meter of pipe. This is a factor of 1.4 higher than the experimental value of 0.0845. The only significant difference is a solid density of 15.22 KN/m^3 for the calculation, compared to 14.5 from the experiment.

It may be noted in Gaessler's Figure 6 that at a Froude number of 3.47, the head loss for pure water is 0.11 m/m which actually exceeds the experimental value (0.0845) calculated for slurry. Therefore, it appears probably that Gaessler assumed a friction factor for water which is too large, or his reported pump head of 5.5 bars is too low.

A plot of head loss vs. concentration is shown in Figure 4 for coarse coal in 196 to 208 mm pipes at velocities of 2.7 to 2.8 m/sec. Gaessler's calculated data are shown at a Froude number of $Fr = 2.75/\sqrt{9.8(0.2)} = 1.96$ from his Figure 6 for 0-60 mm coal.

A review of Traynis' data obtained with a wheel stand may be based on coal data in his Figures 9, 10 and 11. His data in Figure 11 apply to a value of i_o of 0.03 which apparently is for a velocity of 2.7 or 2.8 m/sec in a pipe diameter of 200 mm as indicated by the points on curve 1 of his Figure 8. Traynis' experimental curve 1 for 6-50 mm coal and curve 2 for 0-25 mm coal from his Figure 11 are plotted on Figure 4. Also, three points at $C_s = 20\%$ from Traynis' Figure 10 are included, corresponding to 42% content of three classes of fine coal in the 15-50 mm lump coal. These points are generally consistent with his data from Figure 11, and indicate the decrease in head loss as the smaller classes of coal are added (presumably holding $C_s = 20\%$).

The single point reported by Weber (Ref. Figure 7) for 0-60 mm is shown, which corresponds to his critical velocity of 2.7 m/sec in a 208 mm pipe. This falls close to the Traynis curve for 0-25 mm as well as Traynis' point for 42% 0-1 mm coal in 15-50 mm lumps.

The critical Froude number for run-of-mine coal from Traynis' equation 14 may be written

$$\frac{V_{cr}}{\sqrt{gD}} = \sqrt[3]{\frac{\rho_m-\rho_o}{\rho_m} \quad \frac{0.75\ R_{+3}\left[1.8\ \log_{10} Re - 1.6\right]^2}{(1.9)\ (0.73)}}$$

where $Re = \dfrac{DV_{cr}}{\mu}$ = Reynolds number

and

$0.15 < R_{+3} < 1.00$

If $R_{+3} \leq 0.15$, replace $0.75R_{+3}$ by $(1-2.4\ R_{-3})$

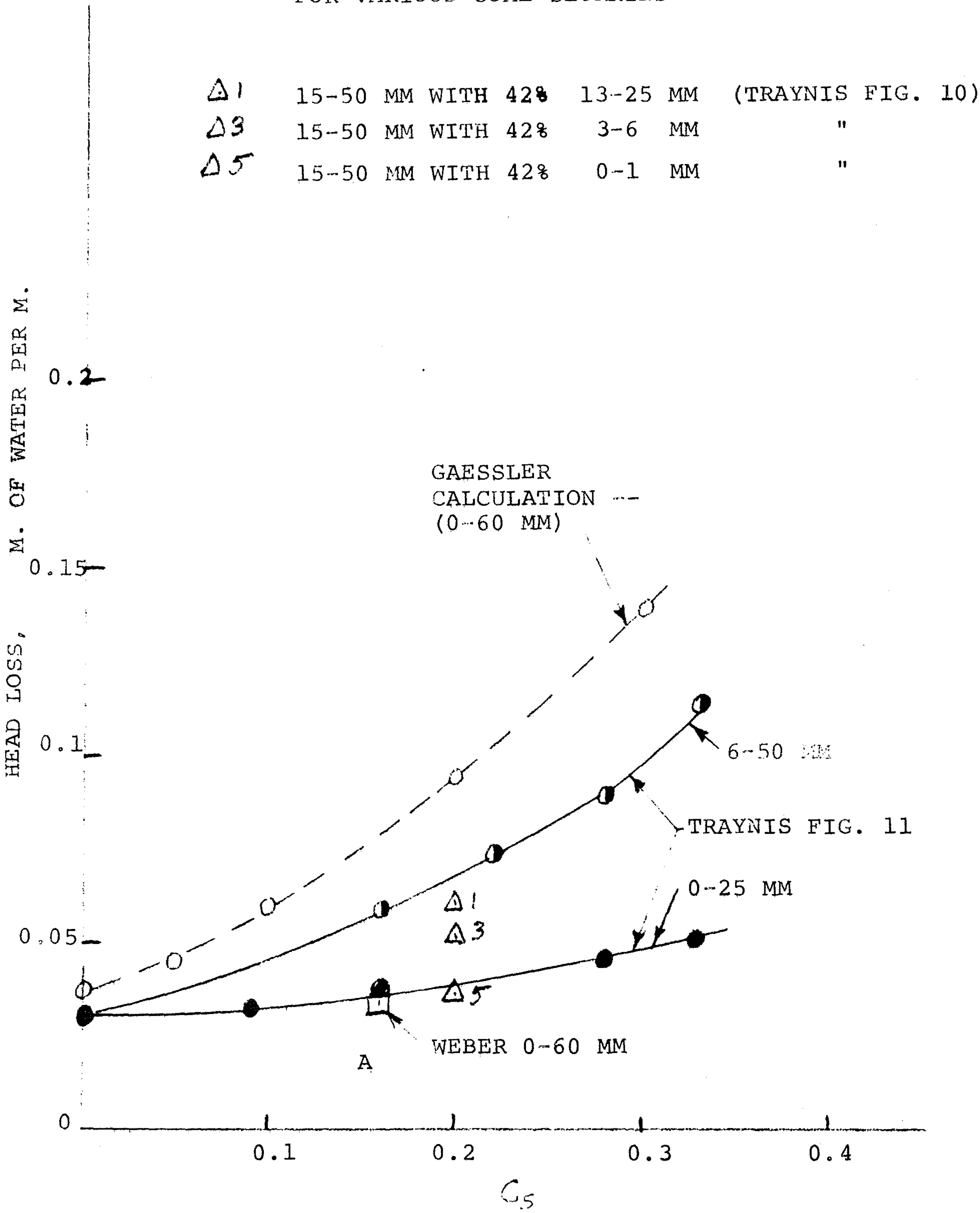
where $R_{-3} = 1 - R_{+3}$

This equation may be solved by iteration. However, a first approximation is to assume a constant friction factor:

$$4\ f = \lambda o = (1.8\ \log_{10} Re - 1.6)^{-2} \simeq 0.0145$$

FIG. 4

COMPARISON OF HEAD LOSS DATA
FOR PIPE DIAMETER OF 196-208 MM
AND VELOCITY OF 2.7-2.8 M/SEC
FOR VARIOUS COAL SLURRIES



for Reynolds numbers of 3 to 7 x 10^5 (as seen in Figure 7 of Traynis).

Therefore, approximately:

$$\frac{V_{cr}}{\sqrt{gD}} = \frac{\rho_m - \rho_o}{\rho_m} \left[\frac{0.75\ R_{+3}}{1.9(0.73)\ (0.0145)} \right]^{1/3}$$

$$V_{cr} / \sqrt{gD} = 3.35 \left[\frac{\rho_m - \rho_o}{\rho_m} R_{+3} \right]^{1/3} \quad \text{for } R_{+3} > 0.15$$

Curves of this equation are plotted in Figure 5 for three values of the lump coal fraction (R_{+3} = 0.34, 0.41 and 0.85). Experimental points are plotted from Weber and by visual inspection of the minima in Figure 3 of Traynis. Also two of the calculations by Gaessler for coarse coal are plotted.

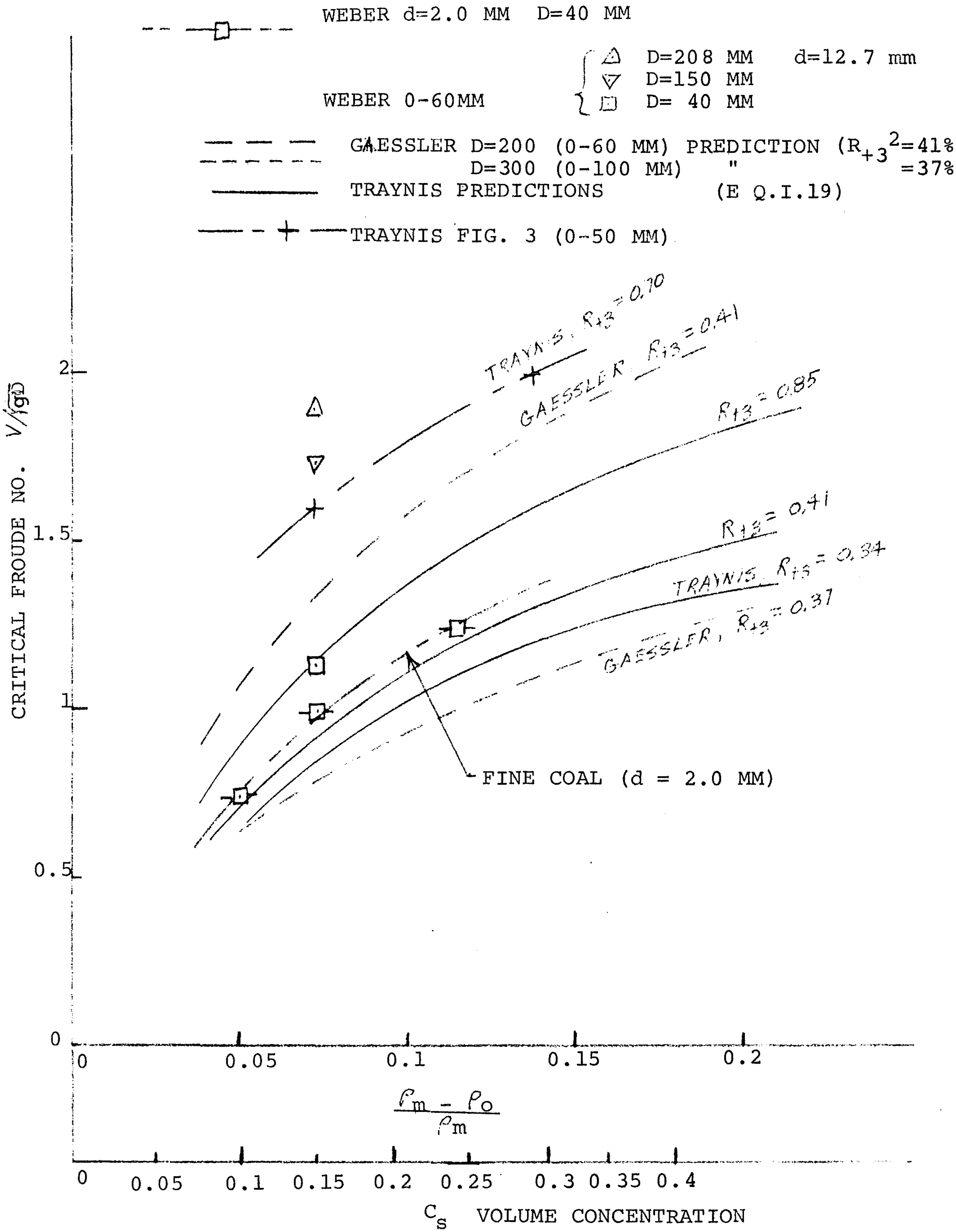
The critical Froude number for 0-60 mm coarse coal in a 208 mm pipe was determined by Weber to be 1.9 at C_s = 0.15. The value reported by Traynis for 0-50 mm coal is about 1.15 (his Figure 3). However, his data can be interpreted to get a higher value of 1.6. The Prettin-Gaessler Figure 6 predicts a critical Froude number of 1.3. However, on their page E2-19 they state that the limiting Froude number for 0-60 mm coal is 3.3 for C_s = 30%., in a 200 mm pipe, corresponding to a velocity of 5 m/sec. This appears to be an excessively conservative value for the critical Froude number and was apparently intended by them to represent an estimate of a worst case for the particle density and size distribution.

The following conclusions appear to be warranted concerning critical velocities:

1. By analyzing Traynis'equation I.19 using a constant friction factor (λ_o = 4f = 0.0145), the predicted values of critical velocity for coarse coal (over 70% + 3mm) appear to be too low by a factor of at least 1.2 and possibly 1.4 or more. (In fact, Traynis implies on Page 39 that his equation I.19 gives critical velocities smaller by "a reserve factor of 1.2" than the lowest experimental velocity, apparently due to the danger of plugging of the experimental pipes at lower velocities).

FIG. 5

CRITICAL FROUDE NUMBER
VS CONCENTRATION
(DENSITY 1.52 GM/CC)



2. The Gaessler analysis for 0-60 mm coal with 41% lump coal (3-60 mm) predicts critical Froude numbers about 35% to 40% higher than the Traynis equation. However, the Gaessler analysis for 0-100 mm coal in a 30 mm pipe gives lower values than the Traynis analysis for similar lump fractions (37% and 34% respectively). Therefore, the Gaessler analysis appears to be inconsistent.

3. Since Weber did not report the size distribution of the coal for his Figures 7, 10, 11, and 14, it is not possible to apply the Traynis analysis which requires knowledge of the lump fraction over 3 mm size.

4. More accurate application of the Traynis equation will require data on the friction factor of the pepe and its variation with Reynolds number.

III.4 LUMP SIZE DEGRADATION

No non-Russian data were found on size degradation of lump coal during hydrotransport through pipes. Therefore, the data presented by Traynis (in his Figure 12 and Chapter 2) experiments in a wheel stand, where crushing of coal by passage through pumps was avoided. The tests included various grades of bituminous coal and anthracite for simulated distances up to 50 km.

III15 PIPE EROSION-CORROSION

Traynis (Chapter 3, Ref. 9) conducted experiments on abrasive wear in a wheel stand (2.6m diameter) with a pipe diameter of 200 mm. A copper insert section was mounted flush with the pipe wall. It had a weight loss twice that of Russian type 3 steel. In order to accelerate testing, most tests used rock crystal instead of coal. Distances of up to 400 mm were simulated. It was concluded that the maximum wear of a pipe carrying coarse coal will occur at a distance of 5 to 10 km along the pipe.

In Traynis' Table 7 (page 95) are included data on pipe wear by anthracite and bituminous coal. These data for pipeline lengths greater than 12 km were plotted vs. length and extrapolated to predict values of $(1/\ \overline{\pi})$, which is the maximum wear depth (mm per 1000 metric tons of coal), which apply for pipe lengths of about 5 to 12 km. This was multiplied by 10^3 to get mm per 10^6 metric tons ($\Delta\ S_{max}$), for comparison with the data of Prettin and Gaessler (Ref. 14).

Despite the statement by Traynis (p.97) that the pipe wear is proportional to velocity to the 0.85 to 1.0 power, the limited data seem to correlate well with the cube of the Froude number as seen in Figure 6. The equation of Prettin for maximum wear is

$$\Delta S_{max} = 0.97\ Fr^3$$

which plots as a horizontal line in Figure 6 and compares well with two points by Traynis for coarse bituminous coal. (It is assumed that all the Traynis data points were obtained in a 0.2m pipe at a Froude number of 2 and velocity of 2.8m/sec.

The three points for anthracite seem to vary linearly with ash content, indicating a relationship of the form.

$$\frac{\Delta S_{max}}{Fr^3} = 1 + 15(X - 0.05)$$

where X = fractional ash content in anthracite

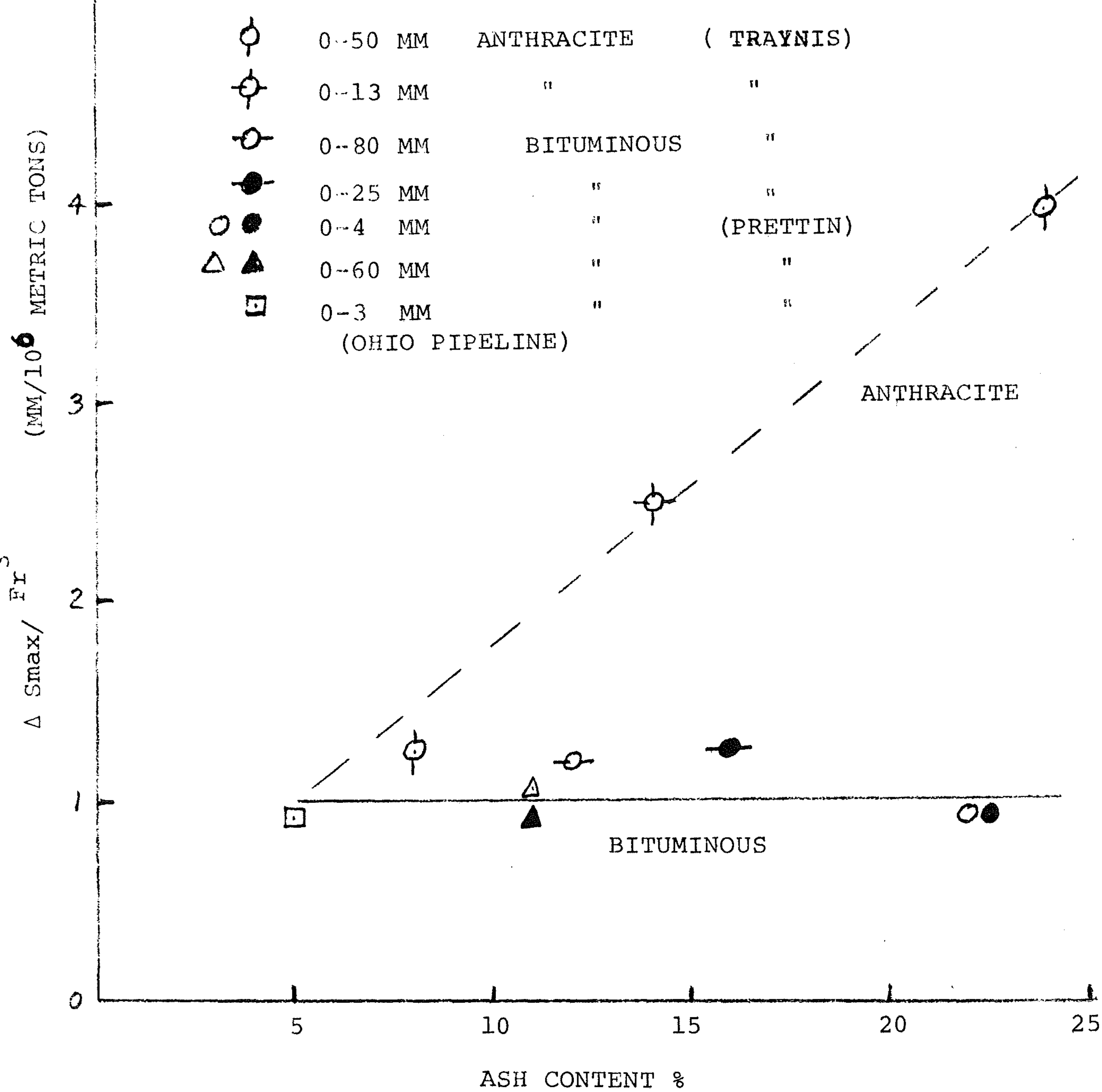
In actuality it is probable that the relationship is more complex since it involves the size distribution of the coal, the hardness of the steel pipe, the hardness of the coal lump impurities, etc. Furthermore, the Prettin point for the Ohio pipeline has not been corrected to apply to short pipelines of the same (1 to 12 km) length, although presumably, the wear depth was selected at the worst point.

One may hypothesize that the wear ΔS may actually vary with the first power of velocity for Froude numbers near critical but with an increasing power of V_m up to the third power at high velocities.

FIG. 6

MAXIMUM WEAR OF PIPELINES (1 to 12 KM LONG)

AS FUNCTION OF ASH CONTENT IN COAL



IV. CONCLUSIONS

1. The book by Pokrovskaya is a welcome addition to the world literature on slurry transport. It deals primarily with slurries of minerals, rock and tailings and with only limited reference to coal. It includes excellent presentations of the subjects of slurry flow regimes, cavitation, pumps, homogeneous slurry structure, erosive wear and operational techniques. The treatment of these subjects is much better than presently available in Western literature. The major criticism of the book is the lack of clarity in the graphs and tables and the frequent failure to report the relevant details of experiments from which the data were obtained.

2. The book by Traynis is an excellent review of the extensive research in the USSR on hydrotransport of coal, with emphasis on coarse coal. It deals with correlation of data on headloss, deposition velocity, lump degradation, erosive wear and rheology of fine coal suspensions. It reports a potentially outstanding contribution to slurry pipeline technology, which is the development of the wheel stand as a pipeline flow simulator by Traynis and Rukov in 1966. The wheel stand is a circular doughnut-shaped pipe which is partially filled with slurry and rotated around a horizontal axis to cause relative motion of the pipe and slurry, simulating flow in a horizontal pipe. Rotational power input is a measure of the headloss. Tests have validated that if the pipe volume is less than one third filled with slurry, the wheel stand provides a very good simulation with respect to predicting pressure drop, deposition velocity, degradation of lumps, and wear of the pipe as compared to a horizontal slurry pipe. Data are presented for slurry specific gravity up to 1.2. The wheel stand has the advantage of not subjecting lumps to degradation by multiple passage through a pump, as in a pipe loop test. The wheel stand permits large amounts of test data to be acquired rapidly with relatively small inexpensive equipment.

3. Chapter IV of the book by Nurok contains a good summary of the extensive work by Traynis on hydrotransport, as well as a discussion of Soviet developments of centrifugal slurry pumps. This indicates that large centifugal pumps, including two stage pumps for coarse coal, are much more fully developed in the USSR than in other countries. Centrifugal pumps for coal can operate at higher speeds and produce higher head per stage than is general practice in the U.S. for slurry and dredge pumps which are designed to handle more abrasive materials.

4. Based on the limited test data available, the Traynis equation I.18 appears to predict head loss quite well for coarse coal slurries. The analysis by Prettin and Gaessler for 0-60mm coal predicts head losses which appear to be too high.

5. The Traynis equation I.19 for critical velocity, when analyzed assuming a constant friction factor for water of $\lambda_0 = 0.0145$, predicts critical velocities for lump coal which are too low by a factor of about 1.2 to 1.4 or more. More detailed analysis of the equation is needed to take into account the friction factor and its variation with Reynolds number.

6. Gaessler's analytical predictions of critical Froude number for 0-60mm coal fall closer than Traynis' equation I.19 to the experimental data of Weber. However, the complexity of the Gaessler analysis makes it less desirable for prediction than the Traynis equation, which should be modified by an upward correction factor of 1.2 to 1.4.

7. The three books reviewed are unique and useful additions to the world literature on hydrotransport.

8. Graphical data are presented by Traynis which suggest that headlosses for coarse coal transport can be predicted with good accuracy for pipe sizes up to 14 inches in diameter. According to the authors, such tests can be performed more rapidly and economically in wheel stands than in pipe loop tests, and with the added advantage of avoiding lump degradation by successive passages through centrifugal pumps.

V. RECOMMENDATIONS

1. The English translation of the books by Pokrovskaya and by Traynis should be published and made available for access by research and engineering personnel in Western countries.

2. Further development and refinement of the wheel stand as a method for studying slurry flow and pipe wear characteristics should be conducted. A primary application will be to obtain data on erosive wear of pipes and pipe lining materials with various slurry materials. Because of the effects of ash content on pipe wear and lump degradation, it is desirable to conduct further tests to measure these effects for typical American coals. Such tests should be conducted in wheel stands to avoid lump degradation by pumps, but the results should be compared with data obtained in large diameter horizontal pump test loops.

3. Acquisition and analysis of additional existing test data should be conducted. The primary sources for existing data on coarse coal hydrotransport are in the USSR, Germany, and the Consolidation Coal Company in the U.S. Additional data should be analyzed and compared with the Traynis correlation equations.

4. System studies and related research and development should be conducted to determine the feasibility of optimizing the overall power generation process, including coal mining, hydrotransport and utilization of coal slurry, including the possibility of direct slurry combustion in boilers. Two of the key technical problems are optimization of the coal slurry properties, and prevention of excessive NO_x production from slurry combustion. In addition, the feasibility of using centrifugal instead of reciprocating pumps for long distance coal slurry pipelines should be investigated as a means of reducing costs and pump maintenance requirements.

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