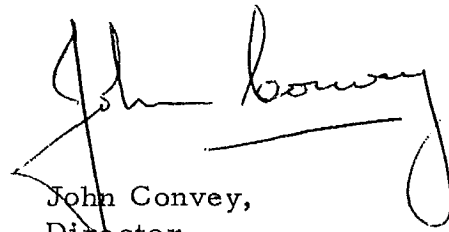


FOREWORD

Increasingly the resources of the Mining Research Centre of the Mines Branch are being employed in appraising the potential application of advanced technology to mining operations. In some areas, projects are concerned with synthesizing existing information through system studies into computer programs that can readily be used by engineering staff on mining properties. In other cases, extensive reviews are prepared and, with a miner's orientation, compilations made of the pertinent features.

Pipeline transportation of solids is such an area of advanced technology where much information exists throughout the world and in many different activities. Because pipelining is not labour intensive, is a continuous operation, and requires relatively low maintenance, it is attractive to the mining industry. However, problems exist, and it was therefore considered of value to make a review of existing information on this subject for the use of mine managers having to make investment recommendations.



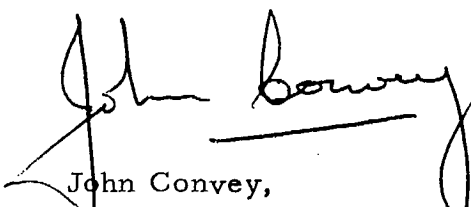
John Convey,
Director.

Ottawa, October 1969.

AVANT-PROPOS

De plus en plus on fait appel aux services du Centre des recherches minières de la Direction des mines pour étudier les applications possibles des progrès techniques aux opérations minières. Dans certains domaines, il s'agit de faire la synthèse des données existantes au moyen d'études de systèmes, afin d'établir des programmes d'ordinateurs aisément utilisables par le personnel techniques des exploitations minières. Dans d'autres cas, on passe en revue la documentation existante afin d'en extraire les renseignements utiles au personnel minier.

Le transport des solides par pipe-lines est l'un de ces domaines techniques où il existe une importante documentation à l'échelle mondiale et qui a de multiples applications. Il intéresse l'industrie minière parce qu'il exige peu de main-d'oeuvre, il permet un fonctionnement continu et demande relativement peu d'entretien. Il pose cependant certains problèmes et c'est pourquoi on a jugé utile de rassembler toutes les données existantes à ce sujet, à l'intention des responsables des mines qui doivent recommander des investissements.



John Convey,
Directeur.

Ottawa, octobre 1969.

Mines Branch Information Circular IC 230

TRANSPORT OF SOLIDS IN PIPELINES, WITH SPECIAL REFERENCE
TO MINERAL ORES, CONCENTRATES, AND UNCONSOLIDATED DEPOSITS
(A LITERATURE SURVEY)

by
A. L. JOB*

ABSTRACT

Pipelines offer significant possibilities for improved transport in the less developed areas of the world. The advantages and disadvantages of transport by pipeline are considered and comparisons made with rail transport. The application of transport by pipeline to the following industries is briefly reviewed: crude oil and natural gas, coal, mineral ores, industrial minerals, and wood pulp. Sand fill in mines, vertical hydraulic transport in mines, and dredging operations requiring the use of long pipelines, are reviewed.

The economics of various lines are reviewed and costs are given for transport of coal, rock phosphates and gilsonite. Transport by pipeline is used extensively in the Florida phosphate fields, and practice in that area is also reviewed.

Vertical transport, as applied to mineral ores and coal, is examined in some detail and feeders are described. Large-scale dredging operations are further described. Pipeline wear, deflocculants, friction-reducing agents, and rifled pipes are mentioned. Centres for research in hydraulics and pipelining are listed and the work of the Alberta Research Council is described.

Tables include a list of mines using vertical transport and a list of pipelines transporting solids in various parts of the world, over 2 miles in length. The technical terms commonly used in the literature dealing with hydraulic transport are defined. A bibliography of 383 references is included.

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Direction des mines

Circulaire d'information IC 230

LE TRANSPORT DE PRODUITS SOLIDES PAR PIPE-LINE, NOTAMMENT
DE MINERAIS, DE CONCENTRÉS ET DE DÉPÔTS NON CONSOLIDÉS
(ÉTUDE DOCUMENTAIRE)

par

A. L. Job*

RÉSUMÉ

Les pipe-lines offrent d'excellentes possibilités d'améliorer le transport dans les régions sous-développées du globe. L'auteur passe en revue les avantages et les désavantages du transport par pipe-line par opposition au transport ferroviaire. Il examine brièvement l'application de ce mode de transport aux industries du pétrole brut et du gaz naturel, de la houille, des minerais, des minéraux industriels, du bois et de la pâte de bois. Il mentionne le remblayage au sable des vides d'exploitation minière, le transport hydraulique vertical dans les mines et le dragage nécessitant l'emploi de longs pipe-lines.

L'étude examine les aspects économiques de plusieurs genres de pipe-lines et les coûts de transport pour le charbon, la roche phosphatée et la gilsonite. Vu l'emploi généralisé des pipe-lines dans les mines de phosphate de Floride, elle passe en revue les méthodes appliquées dans cette région.

L'auteur étudie en détail le transport vertical, appliqué au minerai et au charbon, et décrit les conduites d'alimentation. Il donne plus de précisions sur le dragage à grande échelle. Il mentionne l'usure des pipe-lines, les produits de défloculation, les agents antifriction et les conduites à rainures. Il énumère les centres de recherche en hydraulique et en canalisations et décrit les travaux du Conseil de recherches de l'Alberta.

Dans les tableaux, on trouve une liste des mines qui utilisent le transport vertical et une liste des pipe-lines de plus de 2 milles de longueur transportant des produits solides dans diverses parties du monde. L'étude comprend également un glossaire des termes techniques couramment employés dans les ouvrages traitant du transport hydraulique, ainsi qu'une bibliographie de 383 ouvrages.

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I. GENERAL REVIEW

Horizontal Pipeline Transport

Solids pipelines are at present transporting in Canada and the U.S.A. approximately 100 million ton-miles of bulk commodities per annum, and by 1980 this figure could reach 8 billion ton-miles (43, 144, 186).^{*} Materials being transported are mainly products of mines and forests. Pipelines offer significant possibilities for improved transport in the less developed areas of Canada where the terrain is rugged and other means of transport may be high in cost or non-existent. Pipelines can cross most terrains and have the advantages of low operating and maintenance costs, dependability, and continuous operation. Little is known, however, of the effect of very low ambient temperatures on pipelines carrying solids in water, nor of the effect of heat transfer from pipe to ground in regions of permafrost. Fixed capital charges account for 70-75% of the total transportation costs, making pipelines particularly insensitive to rising labour costs.

Railways have been able to drop their rates with the development of unit trains (see Table 1). Some of the most effective unit trains in service today are a joint venture by shipper and railroad: the shipper owns the cars and loading/unloading facilities, and the railroad owns the motive power and operates the train. Such competition is said to have resulted in the closure in 1963 of the 108-mile coal-slurry pipeline to Cleveland.

TABLE 1

Representative U.S. Transportation Rates (186)

(For volume of 2 million tons per year and distance of 200 to 500 miles, in cents per ton-mile)

<u>Railroad:</u>	Standard	0.9-1.4	
	ΔUnit Train	0.5-0.9	includes charge for car ownership, excludes loading-unloading charges
<u>Petroleum Pipeline:</u>		0.2-0.5	
<u>Slurry Pipeline:</u>		0.7-1.1	includes preparation and recovery charges
		0.3-0.7	does not include above
<u>Truck:</u>		5.0-8.0	one-way haul, empty return

ΔIndications are that rates for coal from Rocky Mountain foot-hill deposits to Vancouver will be about 0.52 cent per ton-mile (see Can. Mng. Met. Bull., p. 982, Sept. 1969).

^{*}Numbers in brackets refer to items listed in the Bibliography of this report.

Nevertheless, in the United States a new 273-mile coal-slurry pipeline will be in operation by 1970, and a second, 350-mile line is proposed. The Southern Pacific Company has built a petroleum products pipeline on its rail-line right-of-way. An already acquired right-of-way with pipes laid close to an existing track gives railways a considerable competitive advantage if they should wish to enter into the pipeline transport business.

The preparation of the slurry by grinding the mineral or ore to a fine state, and recovery of the solids at a later stage, represent a considerable proportion of total transportation costs, and if this reduction to a fine state is not normally a necessary part of the mineral or ore processing, then in all probability the transport by pipeline would be uneconomic. The transport of coarse materials over long distances requires high velocities, with resultant high power costs and excessive pipe wear. The transport medium used is generally water and this must be available in adequate quantities at low cost. Under certain circumstances this water could, after removal of solids, be sold and used for industrial or agricultural purposes.

Capsule piping has received considerable attention, and it seems that materials such as coal and sulphur may in the future be transported as slugs or in capsules in oil pipelines, the supporting fluid being the oil. Problems arise here in inserting the slugs or capsules into the line and obtaining recovery at the desired point; however, it is believed these can be overcome.

The following generalizations in respect of transport of materials by pipelines may be made, but it is important to note that each project will have special conditions which will result in wide variations in cost and hence in competitiveness with alternate means.

Pipelines may be more economical than railroads when any or all of the following conditions occur:

- (1) No other transport exists.
- (2) Volumes between origins and destinations are large and steady.
- (3) Pipelining offers a more direct route (especially over rugged terrain).
- (4) The solid is reduced to a slurry of fine particles as part of its normal processing.
- (5) Water for transport is readily and cheaply available.

Unit cost of transportation is quite heavily dependent upon throughput - an increase from 2 to 3 million tons per year could result in a 30% decrease (186). Optimum conditions for slurry transport are considered to be over distances of 500 or more miles, and large throughputs of 5-6 million tons per year. Estimates as low as 0.5¢ per ton-mile for total transportation costs have been made for such conditions, and estimates of 0.3¢ per ton-mile have been made for iron-ore slurries. There seems to be little published information on costs for long pipelines in actual operation. In the remote areas of northern Canada it is possible that combined transport (pipelines for ore

concentrates, air transport for personnel and special freight, and bush road haulage for heavy equipment and supplies) could be cheaper than building and maintaining a long-distance railroad.

Studies made by Canadian railway engineers (278) indicate that transportation costs per ton-mile for pipelines are competitive under the following conditions:

Tons per year	Competitive with Railroads over:
500,000	All distances
1,000,000	Distances over 70 miles
2,000,000	Distances over 150 miles
5,000,000	Distances over 250 miles
10,000,000	About the same over 300 miles or more

These figures assume new branch line construction rather than transport by existing lines. Some of the recent iron-ore projects envisage transport of up to 4 million tons per year. It will be noticed that for tonnages of 1/2 million per annum the pipeline is competitive with railroads over all distances, whereas for increased tonnages the pipeline is competitive only over longer distances. This is explained by the fact that slurry-line construction costs vary more directly with volume change than do those of railroads. Costs of the latter are relatively insensitive to volumes, unless these are considerably greater than 10 million tons per annum. There are a multitude of variables in any specific project; however, generalized studies of this nature serve to draw attention to the relative competitiveness of the two systems under "average" conditions.

An engineering firm which has made studies for slurry-pipeline transport of rock-salt crystals, limestone, sand, ore and coal in a number of countries, has often found the technical feasibility was less in doubt than the economic feasibility (206). Long-term adequacy of supply or of market, rather than relative transport costs, was most critical.

Dense slurries of fine particles exhibit fluidities approaching water, so that a hydraulic gradient of 1% is usually sufficient to maintain adequate flow velocity (67). This ensures low unit-cost of transportation, and a ton of fine slurry can be moved about 25 miles for an expenditure of 1 kwh. A further advantage gained in mountainous terrain is that the potential energy of the slurry at the top of a hill is converted largely to pressure energy at the bottom and is available to lift the slurry over the next hill. In transport systems such as rail or road, the potential energy of elevation is wasted on braking.

Table 2, which follows, lists sixty-two solids-carrying pipelines in various parts of the world, two or more miles in length. The figure of two miles is an arbitrary one and has no particular significance.

TABLE 2

Long-Distance Solids-Carrying Horizontal Pipeline Systems

(Two or more miles in length)

Solids Transported	Line Length (miles) Pipe Diameter (inches)	Company and Locality	Size of Solids	Slurry		Flow Velocity (fps)	Pipe Line Capacity	Pumps Used	Present Status (if known)
				% solids by weight	sp gr (a)				
Coal	108 10"	Consolidation Coal Co. From Ohio Coalfields to Cleveland on Lake Erie, U.S.A.	To 14 mesh	50 to 60	1.15 (1.4)	4½ to 5-1/4	1.3 million tons p year (150 tons p hour)	Duplex double-acting, 3 pumps per station at approx. 30-mile intervals	Operated 1956-63. Closed due to lowered rail freight rates
Coal	273 18" and 12-3/4"	Black Mesa Pipe Line Inc (Subsidiary of S. Pacific Pipe Lines Inc.) and Peabody Coal Co., Ariz., to Nev.-Calif. border, U.S.A				6	Init. 4.8 mill. tons p yr, later 6 mill. (117 mill. tons over 35 yrs) 660 tons p hour	Total of 13 4500-gpm duplex pumps. Four pumping stations	Operating by 1970. Cost \$200 million
Coal	350 20"	Consolidated Coal Co. and Texas Eastern Transmission Co., W.Va. to N.Y. City and Baltimore Area, U.S.A.					10 million tons p year		Proposed
Coal	38 12"	Novovolynskaya Mine, USSR	-1/32"	50		4-3/4	220 tons p hour		Operating. Built 1957
Coal	5½ 15"	Houillères du Bassin de Lorraine, Carling, France	16 mesh	25 to 30		7 to 10	250 tons p hour (1½ million tons p year)		Operating since 1952
Coal	490	Cascade Pipeline Ltd., E. Kootenay, B.C., to Vancouver, B.C., Canada							Cost \$200 million. Proposed by CPR, 1969
Coal	126 10"	Polish Central Mining Industry, Poland	to 2"						Operating
Soot and Cinders	3	Kincardine Power Station, UK	to 2"				240 tons p hour		Operating

Gilsonite (an asphaltite)	72 6"	American Gilsonite Co., N.E. Utah to Grand Junction W. Colo., U.S.A.	+95% of -8 mesh	48	1.02 (1.54)	3.9	1200 tons p day	Duplex plunger 4½" x 18"	Started 1957. Still operating
Coal, Sulphur, Gypsum	600	General Commodities Pipe Line Ltd., Edmonton to Van- couver, Canada					6 million tons p year		Proposed
Elemental Sulphur	1600	Pembina Pipe Line Ltd., Alberta to Great Lakes, Canada							Proposed
Sulphur in Oil	750 12"	Commercial Solids Pipe Line Co. Ltd. Proposed by Shell of Canada - Calgary to Vancouver, Canada							Incorporation approved by Parliament in principle. Proposed operation by 1970
Potash Slurry in Brine	377 915 8" 10"	Prairie Commodities Pipe Line Ltd. 8" line from Regina and Saskatoon to Esterhazy 10" line Esterhazy to Chicago. Canada & USA					2 million tons p year	17 stations 80 miles apart	Construction permit applied for
Potash Slurry in Water	1100	General Commodities Pipe Line Ltd., Saskatoon - Edmonton - Vancouver, Canada					2 million tons p year		Proposed
Ground Chalk	57-1/3 10" 8-3/4 n.k.	Rugby Portland Cement Co., Kensworth Quarry to Rugby; do-Rugby to Southam, UK	-30 mesh	55 to 50	(2.7)	3.6	200 tons p hour	Plunger type	Operating. Cement works at Rugby and Southam
Ground Limestone & Clay	6 8"	Trinidad Cement Ltd., Trinidad	48 mesh	48	(2.7)	4	50 tons p hour	Piston type	Operating
Limestone	9.2 5"	Columbia Cement, Columbia, S. America	to 100 mesh	55	(2.7)		0.35 million tons p year	Piston type	In 1969 had been operating for 22 years
Limestone	42 8"	Washington, U.S.A.	-48 mm	55	(2.7)		1.15 million tons p year	Plunger type	Under construction 1969.

Limestone	17.6	Calaveras Cement, California, U.S.A.							Start construction 1969. Quarry to plant over mountainous country
Diatomaceous Earth & Clay	7-1/2 4-1/2"	Pacific Diatomite Ltd., British Columbia, Canada	-1/10"	10 to 20			10 tons p hour		Building 1967. To cross Fraser River
Kaolin	(c) 11 8"	(b) Englehard Minerals & Chemical Corp., Ga., U.S.A.	-30 microns	25	1.18 (2.58)	4	45 tons p hour	4" centrifugal	Operating since 1951
Kaolin	16-1/3 8"	do	-30 microns	37	1.25 (2.58)	4 to 5.7	72 tons p hour	4" centrifugals in series	Built 1959. Still operating
Kaolin	5 12"	do	-6 mesh	25	1.18 (2.58)	4 to 5.7	150 tons p hour	8" R.L. centrifugals in series	Operating since 1940
Phosphate Rock	(d) 4 16"	American Cyanamid Co., Fla., U.S.A.	to 8"	35	1.3 (2.75)	11.9	853 tons p hour	16" centrifugals in series	Operating since 1949
Phosphate Rock	4 20"	International Minerals & Chem. Corp., Fla., U.S.A.		to 40	1.35 (2.7)	12 to 15	2025 tons p hour	Centrifugal	
Phosphate Rock	4 16"	Mobil Chemical Co. (formerly Virginia-Carolina Chem. Corp.), Fla., U.S.A.	-14 mesh	35	1.27 (2.7)	14	780 tons p hour	Centrifugals	Operating since 1958
Phosphate Rock	5 14"	Mobil Chemical Co. (form- erly Virginia-Carolina Chem. Corp.), Fla., U.S.A.	-14 mesh	35	1.27 (2.7)	9.5	150 tons p hour	12" centrifugal	In operation 1952
Phosphate Rock	2 16"	Armour Agricultural Chem. Co., Fla., U.S.A.	to 6"	25	1.3 (2.75)	12	555 tons p hour	Centrifugal	Operating since 1955
Phosphate Rock	2-1/2 16"	Smith-Douglas Co. Inc., Fla., U.S.A.		35	1.4 (2.7)	12 to 14	853 tons p hour	16" centrifugals in series	Operating since 1960
Heavy Mineral Concentrates	3 4"	E.I. Du Pont de Nemours & Co., Fla. U.S.A.	-40 mesh	40	1.39 (3.4)	8.1	45 dry tons p hour	Two R.L. centrif- ugals each station, at 1700' intervals	Operating since 1955

Heavy Mineral Concentrates (from beach)	3-1/2 6"	Titanium & Zirconium Industries Ltd., Australia			13		24 tons p hour		
Iron Ore Concentrates	52 9"	Pickand Mathers and others, Savage River, Tasmania, Australia	-100 mesh	60 (24 by vol.)	(4.9)	5.5	2-1/4 million tons p year	Four positive displacement pumps in parallel	Started 1967 Max. gradient 10%
Iron Ore Concentrates	140	Anaconda Iron Ore (Ontario) Ltd., Nakina, Ont. to Kama Bay, Ont. (L. Superior), Canada					2.3 million tons p year		Operated test line. Pipeline transport feasible. Now dormant
Iron Pellets	250	Minas Gerais, Brazil					4 million tons p year		Under investigation
Iron Ore Concentrates Coal Slurry	13 4" 4 6"	Imperial Metals & Power Ltd British Columbia, Canada					270,000 tons p year (iron ore concs)		Planned 1969
Concentrates	7	U.S. Steel Corp. & Phillips Bros., (Matilde Mine), Bolivia					100,000 tons Zn conc. + 10,000 tons Pb conc. p year	Gravity ?	Concs. to port on L. Titicaca (12,500 ft. elev.), dewatered, loaded on rr trucks, and shipped across Lake; thence rr to Peruvian seaport
Nickel and Copper Concentrates; Mill Tailings	2 lines of 7 1/2 mi. each, 8" 2 lines of 4-1/2 mi. each, 13"	The International Nickel Co of Canada Ltd., Creighton to Copper Cliff, Ont., Canada	6% + 100 mesh 35% + 100 mesh	28 45		6 6	2,000 tons p day 10,000 tons p day		} Operating. Extra lines are stand-bys. All lines are wood stave.
Copper Concentrates	14 6"	From Anaconda Co. El Salvador Mill to railhead at Llanta, Chile	to 14 mesh				800 tons p day		Operating since 1959. Planned 60-mile gravity extension to coast for 2000 tons p day
Iron Ore Tailings	2-1/2 3-1/2 19-1/4"	M.A. Hanna, Minn., U.S.A.	-65 mesh	10 to 12	1.9 (3.3)	7.2	197 dry tons p hr per pipe	12" R.L. centrifugals, one per pipe	Operating since 1959

Iron Ore Tailings	3-1/3 16"	M.A. Hanna Co., U.S.A.	-20 mesh	13 to 20	1.07 (3.4)	9.6	233 dry tons p hour	12" R.L. centrifugals in series	Operating since 1955
Iron-Ore Tailings	2 11-1/2" ID	Hanna Mng. Co., National Taconite, Keewatin, Minn., U.S.A.	50% to 60% - 325 mesh	35-55	(3.0-3.1)	15	650-750 tons p hour	Centrifugals, 14" x 12". Three main and two booster pumps.	From plant to booster station, 5600 ft.
Copper-Ore Tailings	2 16"	U.S.A.	16% + 65 mesh	43		9.92	28,000 tons p day	Gravity ?	Total of 25,000 ft Transite piping in use
Sulphide-Ore Flotation Tailings	44 12.55" OD	Group of mines & mills in Hokuroko District (Dowa Mng. & Nippon Mng.), Japan	90%- 400 mesh	18.8 (mean)	1.14 (1.57?)	4.3	40,000 tons p month	Three Mars double- acting duplex re- ciprocating (one is stand-by), 739 gpm each	Pumped at constant viscosity - not at constant concentration. Control by viscometers & computers
Concentrator Tailings	Three lines each 3 1/2 mi. 20"	Anaconda Co. C.E. Weed Concentrator, Butte., Mont., U.S.A.	21 1/2% +65 mesh	30	1.233 (2.7)	9.33	25,000 tons p day p line	Three 20" RL cen- trifugals in series plus 4 at booster (for each line)	One line is stand-by. Booster station is at mid-line
De-Slimed Flotation Tailings	7 20"	Anaconda Reduction Works, Mont., U.S.A.					20,000 tons p day (for dam building)	Three 20" R.L. centrifugals	Closed 1964
Sand Tailings	2 5"	Bunker Hill Mine, U.S.A.		40	1.35	5 1/2	42 tons p hour	Four 6" centrifugals in series (1st stage)	Two 6" for 2nd stage (1000 ft length)
U-bearing Gold Slimes	6 9"	Loraine GML to Freddie's Consol. ML (N.), S. Africa	95%-48 mesh & over 50% - 200 mesh	50	1.46 (2.7)	4.35	Delivered 63,000 dry tons p month	Four 6" R.L. cen- trifugals in series	No U production at present
do	5 12"	Freddie's Consol. ML (N) to Freddie's Consol. ML(S), S. Africa	do	50	1.46 (2.7)	3.78	176,000 dry tons p month (deli- vered 60,000 dry tons p month)	Three 8" R.L. cen- trifugals in series	do

U-bearing Gold Slimes	7 16"	Freddies Consol. ML(S) to Welkom GMCL, S. Africa	95%-48 mesh & over 50% - 200 mesh	50	1.46 (2.7)	3.96	249,000 dry tons p month (deli- vered 120,000 dry tons p month)	Three 8" R.L. cen- trifugals in series	No U production at present
do	2-1/3 10"	President Brand GMCL to President Steyn GMCL, S. Africa	do	50	1.5 (2.7)	4.54	Delivered 90,000 dry tons p month	Two 6" R.L. centri- fugals in series	do
do	5-1/2 9"	President Steyn GMCL to Welkom GMCL, S. Africa	do	50	1.48 (2.7)	3.7	75,000 dry tons p month delivered & capacity	4" R.L. centrifuga- ls in series	do
do	11-3/4 6"	Babrasco Mines (Pty) Ltd. to Ellaton GMCL, S. Africa	do	50	1.46 (2.7)	3.19	1233 dry tons p day delivered	Five 4" R.L. cen- trifugals in series	Mines closed
do	9-1/2 9"	Ellaton GMCL to Stilfon- tein GMCL, S. Africa	do	50	1.46 (2.7)	3.37	2933 dry tons p day delivered	Six reciprocating pumps, 5" dia x 7" stroke and 7" x 18"	No U production at present
do	6-1/2 8"	Doornfontein GMCL to West Driefontein GMCL, S. Africa	do	50	1.4 (2.7)	2.86	40,000 dry tons p month delivered	2 sets of three centrifugals in series	Operating conditions of line changed later. No U production at present
do	6-1/3 6"	E. Champ D'or GMCL to Randfontein Estates GMC Witwatersrand Ltd., S. Africa	do	50	1.46 (2.7)	3.72	14,000 dry tons p month delivered	Three 4" centrifuga- ls in series	Mines closed
Pyrite Concentrate	2 lines of 3-1/4 each 5"	Merriespruit (O.F.S.) GMCL to Virginia GMCL, S. Africa	-200 mesh	51	1.5 (3.0)	4.5	200 dry tons p day	Four R.L. centri- fugals in series	Virginia still treats slimes
Slurry of Muskeg, Clay, Silt	2.7 32"	Inco's Pipe Mine Site near Thompson, Man., Canada		20			To 60,000 cu.yds. p day. 13 million cu.yds. to be stripped. 35,000 gpm.	Hydraulic rotary cutter dredge stripping lake bot- tom	Operating

Silt, Clays, few Boulders	2 shore lines, 4 mi. each, 42" 2 floating lines to 1 mi. each, 36"	Caland Ore Co. Ltd. (Steep Rock Lake), Ontario, Canada	to 21 mesh			21	5450 cu.yds. p hour each pipe	Two hydraulic rotary cutter dredges stripping lake bottom. Each dredge 36" cent. pump and 10,000 hp motor	161 million cu.yds. moved, 1955-60
Sand, Gravel, Boulder-Clay	Floating, 0.7 mi.; shore, 3.8 mi. Both 32"	Lake Asbestos of Quebec Ltd., (Black Lake), Que., Canada				17	30,000 cu.yds. p day	32" centrifugal. 6000 hp hydraulic rotary-cutter dredge stripping lake bottom	27 million cu.yds. moved, 1954-58
Wood Chips & Pulp	7 18"	Great N. Paper Co., Maine, U.S.A.					150-200 tons p day		Operating
Wood Chips	50	N.W. Pulp & Paper Co., Borland R. area of Alberta to W. of Edmonton, Canada							Projected (1966) but never built

(a) Specific gravity of solids in brackets. Specific gravity of slurry without brackets.

(b) Company has a total of 32 miles of long-distance pipelines carrying de-flocculated kaolin.

(c) There are a number of long-distance pipelines operating in the Georgian kaolin fields.

(d) U.S. rock phosphate production in 1967 was approx. 38.8 million tons. Florida produced approx. 27 million tons. There are some 20 long-distance rock phosphate pipelines in the U.S. - 15 in Florida.

R.L. = Rubber-lined

GMCL = Gold Mining Co. Ltd.

Early Records (206, 207)

The earliest recorded transport of solids in pipelines was in the late 1850's in the California goldfields. Hydraulic elevators - venturi-type devices with nozzles under natural head - raised the water and gravel from the mine bottom to sluice boxes at higher levels. Elevators were in use in Malaya prior to 1900, to lift cassiterite-bearing gravels to sluice boxes; ample supplies of water under natural head could be brought by pipeline from the hills. Other early installations were in Nigeria, Swaziland, South Africa and New Zealand (Otago, 1891). Suction cutter dredges had been in operation on Siberian gold alluvials by about 1897, and in the same decade operated in New Zealand (gold) and Australia (harbour work). A suction cutter was operated in Burma (Tavoy) in 1913, and a number were winning cassiterite in the Malayan tinfields some years later. The suction cutters used for alluvial mining were all eventually replaced by the more efficient bucket dredges.

The first known systematic investigation of hydraulic transport was undertaken by Miss Blatch in about 1908, using sands and working at the University of California. In 1937 Fulson and O'Brien, at the same university, carried out model experiments in 2-in. and 3-in. pipes. In about 1938 G.W. Howard carried out tests with sand and gravel in 4-in. pipes at the Vicksburg Laboratory, U.S.A., and later with rifled pipes. Gregory in 1927 reported experimental tests on pumping clay slurries through 4-in. pipes at concentrations up to 52% solids by weight.

Crude Oil and Natural Gas Pipelines (134,150)

The largest application of pipelines is in the vast and growing network of crude oil and natural-gas lines in many parts of the world. North America is traversed by more than 1 million miles of pipelines, representing an investment of \$15 billion.

North America's first commercial oil well was discovered in the year 1858 in Lambton county, southwestern Ontario.* A wooden pipeline carrying crude oil from the Petrolia Fields of the same county to nearby refineries was in use by 1875. A commercial oil well was brought into production at Titusville, Pa., in 1859; the crude oil was hauled in wooden barrels on horsedrawn wagons. By 1865 a 2-in. six-mile pipeline was in operation here, carrying crude oil to the railroad, and the owner was able to halve the prices charged by the teamsters. The first pipeline undertaken on a continental scale was a 24-in. line, 1,000 miles long, built in 1931 to carry natural gas from the Texas Panhandle to Chicago. World War II provided a stimulus to the construction of pipelines across the U.S.A., as the shipping that carried oil to the Eastern U.S. Seaboard was threatened by German submarines. Since the war almost every crude-oil-producing country has built elaborate pipeline systems over deserts, mountains, or under the sea.

* 'Oil and Gas in Ontario', Dept. of Energy & Resources Management, Toronto, 1967.

Extensive pipelines operate in Russia from the Baku oil fields and natural-gas fields of Siberia, and more are under construction. The recently discovered natural-gas fields in the North Sea are being tapped by pipelines. The cost of constructing pipelines is high - a 36-in. overland line may cost between \$100,000 and \$150,000 per mile (1966) - but, even so, pipelines in North America today carry 20% of all freight moved by land (in terms of ton-miles).

Crude Oil and Natural Gas Pipelines in Canada (338, 356, 360, 361, 375, and Canada Year Book, 1968)

The longest natural gas pipeline in the world has been built in Canada. This is the Trans-Canada pipeline (Trans-Canada Pipelines Ltd.) consisting of 34-, 30- and 20-in.-diameter lines on an all-Canada route extending from the Alberta-Saskatchewan boundary to Montreal via Winnipeg and Toronto. The right-of-way totals 2,462 miles, the pipeline length being considerably greater as some sections of the system have double or triple pipelines. In addition, a 50%-owned affiliate has recently constructed a 971-mile, 36 in.-diameter line from Emerson, Man., into the U.S.A. south of Lake Superior and Lake Huron and thence back into Canada at Sarnia, Ontario.

The world's longest trunk line for moving crude oil is also in Canada: the Interprovincial Pipe Line Company system, made up of pipes up to 34 in. in diameter. The main line of 1,930 miles extends from Redwater, Alta., via Edmonton, Regina, and across the international border at Gretna, Man., to Superior (near Duluth, Wis.) and thence south of Lake Superior and Lake Huron, re-entering Canada at Sarnia and on to Port Credit, Ont. (near Toronto). A lateral line of 95 miles extends from Hamilton, Ont., to Buffalo, N.Y. Some of these lines have also been doubled or tripled. To be completed, by a subsidiary of Interprovincial, is a 754-mile line of 34- and 30-in. pipe from Superior, Wis., to Chicago and south of Lake Michigan, and back into Canada at Sarnia. (The Superior-Chicago section was scheduled for completion in 1968.)

The Trans-Mountain Oil Pipe Line Company's 30- and 24-in. pipeline carries crude oil from Edmonton to Burnaby, B.C. (near Vancouver) in a line 723 miles long. The Westcoast Transmission Co. Ltd. has a 30-in. natural-gas line which extends from Fort Nelson, near B.C.'s northern border, through Prince George to Vancouver, a distance of 866 miles. A further 36 miles of line extends to the Alberta border and a recently completed 450-mile line extends from Summit Lake (north central B.C.) to near Prince Rupert on the coast, with a branch to Kitimat, the aluminum smelting centre. Four oil companies and two pipeline firms have formed a new company to investigate the feasibility of constructing a 48-in.-diameter, 600-mile crude oil pipeline from the recently discovered Alaskan North Slope field (Prudhoe Bay) through Yukon and the Northwest Territories to Edmonton, where it would connect with the Trans-Mountain and Interprovincial systems.

The various lines are interlinked with U.S. systems and almost all are planning, or have underway, extensions to their pipeline systems. The smaller companies not mentioned may have hundreds of miles of lines. As at the end of 1966, pipelines in Canada totalled 32,695 miles, made up as follows:

*Crude oil and natural gas products, trunk lines	8,681 miles
*Crude oil and natural gas products, gathering lines	4,314 miles
Natural gas, transmission lines	14,600 miles
Natural gas, gathering lines	5,100 miles
	<hr/> 32,695

Capsules: Oil, Sulphur, and Potash (93, 186, 339)

Over recent years a great deal of work, initiated by the University of Alberta and the Research Council of Alberta (133, 378, 379), has been carried out on investigations of the pipeline transport of slurries and solids. They have a 3,500-ft loop of 4-in. test line and have also transported 514-lb steel capsules through 109 miles of the Interprovincial 20-in. line (95, 135, 136, 137, 339). Their work indicates that solids in containers or in capsules, or as slugs, could be cheaply transported over long distances in oil or other fluids. Materials which could be transported in large volume are coal, sulphur (111), or potash and grains. Elsewhere, various projects are in the planning or preliminary investigation stages. The most advanced is that of Shell of Canada Ltd. (173, 338, 360, 374, 376) who propose to move sulphur in a 12-in. oil line over a distance of 750 miles from Calgary to Vancouver. The Commercial Solids Pipeline Company has been formed for this purpose and its incorporation approved by Parliament. A more ambitious scheme is that of Pembina Pipelines Ltd. who plan to move sulphur 1,600 miles from Alberta to the Great Lakes for loading on shipboard. Another proposal, by Prairie Commodities Pipeline Ltd. (67), is to move a potash slurry in brine from Esterhazy, Sask., to the Chicago area. General Commodities Pipeline Ltd. (374) plans to move potash slurry from Esterhazy to Vancouver, and coal, sulphur and gypsum from the Edmonton area to Vancouver.

Coal

The earliest long distance lines for the transport of solids were those carrying coal. A short line (1,750 ft) (206, 207) was used in 1914 to move coal from barges on the Thames River, near London, to a boiler plant. A 7-in. sludge pump delivered 50 tons per hour of coal through an 8-in. cast iron bell-and-spigot line. In the mid-1940's a 15-in. line was built in France to carry coal-washery sludge at 25% solids over 58 miles to a power house. This line is still in operation. The Pittsburgh-Consolidations's 108-mile coal-slurry line (117, 206, 212, 303) was first planned in 1949. The slurry was to be transported from the Ohio coalfields to Cleveland. A pilot plant was built and operated during 1951 and 1952, and the main 10-in. line was completed by 1956, but it was not until 1958 that the line was in continuous operation carrying 1 million tons per year. This line operated until 1963, when reduced railway rates caused it to be closed in favour of rail transportation as the

* Estimated total, 1967: 13,620 miles.

railway company was able to improve its methods of operation and design of equipment. There is considerable and renewed interest in the transport of coal by pipeline and The Consolidated Coal Co. is planning a 350-mile, 20-in. line (65) from West Virginia to Pennsylvania, New Jersey, and New York City. The coal would be very finely ground in a water mixture and would be partly dried before burning. A 273-mile, 18-in. coal-slurry line is planned for 1970 by the Southern Pacific Company's subsidiary, Black Mesa Pipeline Inc. The coal will be mined from a Peabody Coal Company mine in northeastern Arizona and transported to a steam plant in southern Nevada.

A 126-mile, 10-in. line operates in Poland carrying coal up to 2-in. size. At the Novovolynskaya Mine in Russia, 220 tons per hour of coal is transported through a 12-in. line over 38 miles. A 490-mile pipeline has been proposed for the transport of a coal slurry from the Kootenay region of British Columbia to Vancouver.

Gilsonite (29, 30, 124, 125, 202, 207, 276, 351)

The American Gilsonite Company has, since 1957, been pumping gilsonite (an asphaltite) through 72 miles of 6-in.-diameter pipeline, at a delivery rate of 1,200 tons per day, from Bonanza Mines, Utah, to the refinery at Grand Junction, Colo. The pipeline reaches an elevation of 8,500 feet at the Baxter Pass. Due to the rugged territory and the length of road which would have been required for overland transport, it was decided that pipeline transport would be the most economical. This system is further described on pages 24 and 40.

Wood Chips and Pulp (186, 220)

Wood chips and wood pulp are being carried by pipelines. The N.W. Pulp & Paper Co. has projected a 50-mile line to carry chips from the Borland River area to west of Edmonton. The Pulp & Paper Research Institute of Canada (358) operated a 2,000-ft. test line at Marathon, Ontario. This project was sponsored by CNR, CPR, four pulp and paper companies, and two pipeline companies. Results indicated that wood chips could be carried in pipelines at low costs from forest to mill. The Great Northern Paper Co. in Maine moves 200 tons per day of sulphide pulp through a pipeline from a pulp mill to a newsprint mill. A 60-mile wood-chip pipeline is planned for use in the Caucasus (USSR).

Kaolin, Chalk, and Diatomaceous Earth (220)

Pipelines for the transport of kaolin slurries are used in Georgia over distances to 16 miles. Finely ground chalk or limestone is also carried by pipelines from quarry to process plants. A 57-mile line (297) near Rugby, U.K., moves ground chalk at the rate of 200 tons per hour. There are no intermediate pumping stations and solids content has exceeded 60%. Pressure is 1225 psi with a velocity of 3.6 fps. Trinidad Cement Ltd. has a 6-mile line in operation carrying ground limestone.

Iron Ore Concentrates

The development of large iron-ore mines in remote interior regions with large outputs has resulted in increased attention to the use of pipelines for transport as against the building of railroads. The Savage River iron mine in Tasmania (190, 209), recently opened, is the first iron mine to use a pipeline for transport of the ore, which is pumped as a slurry to the pelletizing plant 52 miles away in a 9-in. pipeline. Pellet production will be 2-1/4 million tons per year.

Recently developed and used in Peru is the 'Marconaflo Process'. Iron ores are finely ground and slurried and then pumped from shore to sea-carrier with a 75% solids content. The slurry is allowed to settle in the carrier and water is drawn off so that the moisture content is about 8%. At destination, the ore is reslurried by high-pressure water jets and pumped ashore. There is reportedly a very considerable savings in direct power and handling costs by this method over conventional handling methods.

A proposal to move approximately 4 million tons per year of iron-ore concentrates from Minas Gerais (Brazil) to Rio de Janeiro through 250 miles of pipeline is under study. The Anaconda Iron Ore (Ontario) Ltd. is considering pipeline transport for 2.3 million tons per year of iron-ore concentrates from Nakina, Ont., to Kamba Bay, Ont., and in 1961 this company operated a 1,000-foot test loop at Skibi Lake, Ont.

Heavy-Mineral Concentrates

The International Nickel Co. of Canada Ltd., Ontario, (102, 206, 207, 364) moves nickel-copper concentrates and mill tailings by pipeline. The concentrates are moved 7-1/2 miles from Creighton to Copper Cliff in an 8-in.-diameter pipeline and tailings move over 4-1/2 miles in a 13-in.-diameter pipeline. The Anaconda Company transports copper concentrates in Chile from its mill at El Salvador (185) to railhead at Llanta. The distance is 14 miles and the pipeline is 6 in. in diameter. An extension of 60 miles to the coast (a gravity line) is under consideration (65).

Rock Phosphates

Probably the most concentrated and extensive use of hydraulic transport anywhere in the world is to be found in the Florida phosphate fields (36, 65, 97, 120, 143, 222, 285, 286, 290). The ore (matrix) is broken up by hydraulic giants at the mine site and the resultant slurry is pumped up to 6 miles to treatment plants. Matrix pumping systems capable of pumping 25,000 gpm are in use. 18-in. centrifugal pumps may be used, driven by 1,250-hp electric motors, to feed pipe lines up to 20 in. in diameter. The Florida phosphate field produces 26-27 million tons of phosphate rock annually, and it is estimated that, for each ton of rock produced, 3 tons of matrix are pumped to the recovery plant and 2 tons of slime and sand from the plants disposed to waste by pumping.

Uranium-bearing Slimes

With the advent of demand for uranium in the 1950's, some of the South African gold producers were able to treat their slime dumps profitably for the recovery of uranium (47, 108, 242). Pipelines were chosen to transport these tailings over distances of up to 12 miles through lines up to 16 in. in diameter.

Sand Fill, and Tailings

There are very few mines anywhere in the world which do not convey concentrates, tailings, or other products by pipeline. Sand filling usually entails extensive pipelining of sands from the surface to underground sites. On many mines, tailings may be conveyed for miles through pipelines to dams and stacking areas. At the Mesabi Iron Range, Minn., 40,000 tons of tailings are carried daily through nine 12-in.-diameter pipelines up to distances of 40,000 ft.

An interesting recent Japanese installation is a 44-mile, 12-in.-diameter pipeline carrying slimes from ponded flotation tailings to a disposal site (62). The solids are 90 to 95% minus 400 mesh. The pumps used are Mars (made in Japan) double-acting duplex reciprocating; the pistons and cylinders are in contact with oil only, and hence not subject to abrasion and wear from the slurry. The slurry is pumped at a constant viscosity and not at a constant solids content. A sample of the slurry is fed continuously to 2 viscosimeters linked to a computer, and clear water is added automatically as required to obtain the correct viscosity. At the disposal site, the slurry passes through a flocculation tank and clear water from the disposal pond passes through a chemical treatment station to remove metal ions such as lead and zinc. The total cost of the project was \$6.35 million.

Other Materials

A partial list of materials handled hydraulically by pipelines totals 144 (189). These range through various food stuffs, chemicals, chemical waste, industrial waste, sewage, acids, and sugar cane, to mine and quarry products. An unusual application is in the Swiss Alps, where plastic pipelines carry milk from the farms on mountain slopes to cheese factories in the valleys. An immense amount of sewage is carried in pipes and some of the earlier experimental investigations into the flow of slurries were made on sewage muds and sludges.

Vertical Pipeline Transport (25, 38, 42, 57, 167, 194, 217, 240, 382)

Vertical transport (or hydraulic hoisting) (8, 56, 90, 100, 105, 168, 211, 304) in metal mines has received little attention. Bancroft Mine, Zambia (63, 66, 231) hoists about 1/3 of its ore to surface by this means through 1,350 ft. A coal mine in France (51, 73, 74, 175) uses vertical hydraulic hoisting through 590 ft, and coal mines in Poland and China also use this system. In Canada, both Sherritt Gordon Mines Ltd. (366) and Falconbridge Nickel Mines Ltd. have carried out experimental vertical hoisting on a

pilot scale. An experimental system is to be tested at a South African gold mine where fine ore will be pumped through 7,200 vertical feet in four stages.

Dredging

The dredging industry (both on shore for winning minerals and at sea for dredging of harbours, filling, and so on) makes considerable use of pipeline transport. An unusual project (262) is the removal of 3-4 million cu yds of sand to fill an area for a new city in the Bronx area of New York. A shipboard-pump pumps the sand through 3 miles of 26-in. line. At the International Nickel Company's new Pipe Mine site near Thompson, Man., a dredge with a hydraulic rotary cutter is pumping a slurry of muskeg, clay and silt from the lake bottom through 14,000 ft of 32-in. pipe to Upper Oswagen Lake. A large-scale operation was that at Steep Rock Lake, Ont. (22, 223, 248), where 162 million cu yds of material was stripped from the lake bottom to expose the iron-ore bodies. The material was dredged by two suction cutter dredges and pumped through 4-1/2 miles of twin 42-in. pipe. Each dredge pump was rated at 10,000 hp, as were the two booster pumps on each line (a total of four booster pumps).

II. ECONOMICS

Crude Oil and Natural Gas Lines

Representative costs for material and construction of conventional gas and oil lines for the year 1967 were approximately \$13,000 per mile for a 4-in.-diameter line, \$36,000 for a 12-in. line and \$75,000 for a 24-in. line. Table 3 is a breakdown of average pipeline costs for a 5-year period, 1960 to 1964, in terms of dollars per mile of pipeline and dollars per inch²/mile (pipe cross-sectional area in square inches divided into cost per mile). Figure 1 (95) shows graphically construction costs in the U.S.A. and Canada for the year 1966.

TABLE 3

Oil Pipeline Costs (1960-1964)*

Pipe Diameter, in.	Material \$	Right-of-way \$	Installation Labour \$	Misc. \$	Total Cost \$	Total Cost per in. ² /mile \$
6	10,419	1,688	7,550	1,327	20,984	742
8	12,985	2,852	12,394	1,832	30,063	598
12	20,495	233	11,066	1,463	33,257	294
16	29,084	2,204	16,517	2,453	50,258	250
20	36,847	2,501	23,047	4,059	66,454	212
24	55,090	2,533	24,216	3,965	85,804	190
30	68,379	3,779	33,696	5,545	111,399	158
36	96,549	5,763	46,191	8,760	157,263	155

*Source: Hodgson, R.C.A. Rept. No. 277 (1964).

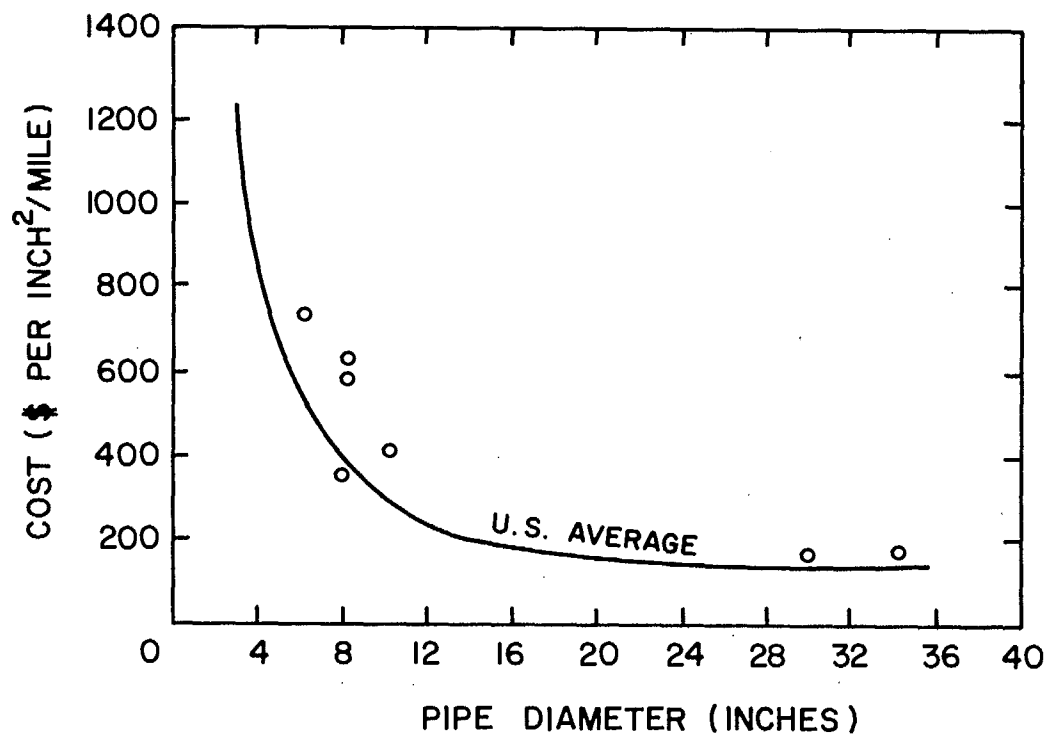


Figure 1. Canadian pipeline construction costs, 1966 (shown by circles). (See bibl. ref. 95.)

Costs of operating the larger oil and gas lines are lowest in the larger diameters. The operating cost of a 20-in. line will be only about 1/3 of that for a 10-in. line and the carrying capacity is increased more than 3 times (43).

Coal and Other Minerals (23, 117, 295, 309)

1. An engineering firm with considerable experience in the design and construction of pipelines has, from time to time, carried out pipeline economic studies (112, 113, 114), and Table 4 summarizes some of its work (circa 1963). It will be noted that there is a wide variation from \$0.0052 per ton-mile to \$0.033 per ton-mile in operating costs. Construction costs varied from \$0.029 to \$0.098 per annual ton-mile. For lines of 8-in. to 16-in. diameter, direct costs (excluding overheads) were \$3,500 per in.-mile (\$28,000 per mile - 8 in., \$56,000 per mile - 16 in.). Figures 2 and 3 show operating costs and investment for coal pipelining, based on these economic studies.

TABLE 4

Solids Pipeline Costs (ca 1963)

Pipe Diameter (in.)	Miles	Annual Tons (millions)	Construction Costs (\$ millions)	Operating Costs (\$ per ton-mile)	Material Transported	Construction Costs (\$ per in. ² /mile)
10	22	2.167	4.7	0.033	Coal	\$ 720
8	97	0.936	6.0	0.017	Coal	1,231
10	97	1.650	7.0	0.012	Coal	919
12	97	2.670	8.8	0.0092	Coal	802
10	155	2.000	13.0	0.0076	Metallic ore	1,068
6	800	1.000	38.0	0.0085	Metallic ore	1,700
8	800	2.500	58.0	0.0052	Metallic ore	1,450

Note: Construction costs (in Table 4) are defined as including installed cost of equipment to grind, pump and dry the delivered solids, as well as cost of buildings. Operating costs include labour costs for maintenance, cost of fuel and power, cost of chemical and replacement supplies, and fixed charges. (112-114)

2. The Consolidation Coal Company (117) operated its 10-in., 108-mile line from 1957 to 1963, and when it closed down had carried over 7 million tons of coal. When the line was first put into operation, freight rates from Cadiz (Ohio) to Cleveland on Lake Erie were \$2.63 per ton, rising later to \$3.47. Closure of the line was due to a reduction in freight rates to \$1.88. The coal was ground to -14 mesh size (about 1/16 in.) and carried as a 47- to 50%-by-weight slurry; later, a stabilized slurry was developed which could be pumped at 60% solids. Corrosion and erosion of the line were much less than anticipated. There were 3 pumping stations which used duplex, double-acting piston pumps driven by 450-hp motors.

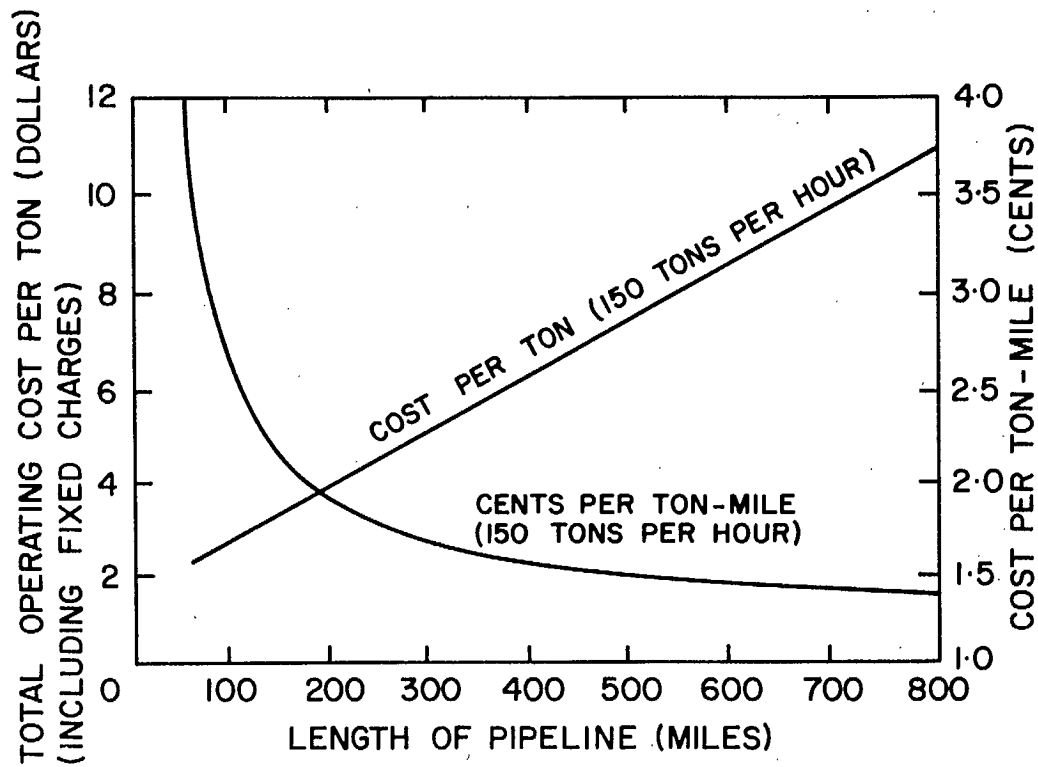


Figure 2. Operating costs for coal-slurry pipeline (150-200 tons per hour, or 1.3-1.7 million tons per year). (See bibl. refs. 112, 114.)

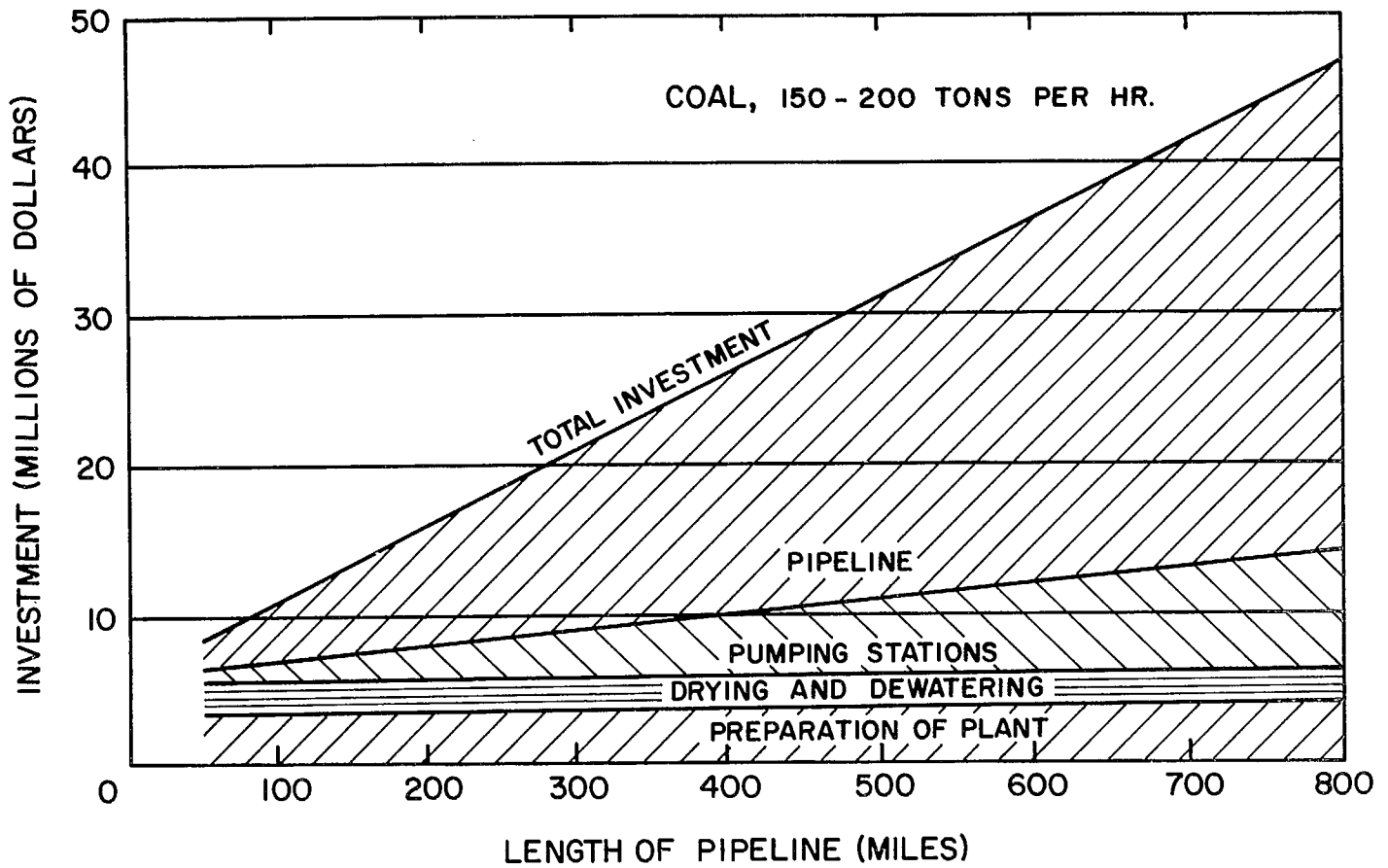


Figure 3. Investment costs for coal-slurry pumping systems. (See bibl. refs. 122, 114.)

Power requirements and costs for the 3 stations are given in Table 5, based on a 9-mil power cost and operating factor of 97% giving an annual delivery of 1,550,000 tons (4,400-tons-per-day capacity). Capital costs are given as \$6½ million.

TABLE 5

Coal Pipeline Costs, U.S.A. (ca 1963) - Power and Pumping

Tons per hour pumped (rated)	150	160	170	180
Million tons per year (actual)	1.2	1.3	1.4	1.5
Horsepower required	2,120	2,410	2,720	3,020
Cost, cents per ton (power)	8.4	9.8	11.3	12.7
Cost, cents per ton-mile (power)	0.078	0.091	0.105	0.117

Pumping costs at a rate of 4,400 tons per day are: -			
	<u>¢ per</u> <u>ton</u>	<u>¢ per</u> <u>ton-mile</u>	
Power	13.1		
Inhibitor	1.5		
Operating labour	2.1		
Maintenance labour	1.5		
Supplies	5.5		
Miscellaneous	1.8		
Labour burden, taxes	<u>4.5</u>		
Total	30.0	0.275	
Add capital charge of 15%	<u>63.0</u>	<u>0.585</u>	
	93.0	0.860	

3. Detailed cost estimates (circa 1962) are available based on results of operating The Consolidation Coal Company's slurry line and from extensive preliminary work in their loop of 10-in., 12-in. and 16-in. pipe (117, 295, 309). Table 6 gives a breakdown of costs for 3 million metric tons per year of coal as a 60%-by-weight slurry transported over 200 miles in a hypothetical 14-in. line. The pumping stations are automated and the total horsepower for 5 stations is 11,000. There are 2 operating and one spare pump at each of the five stations. The cost of power is 1.1¢ per kwh. The item "Chemicals" is for corrosion protection of the pipes. Operating cost (exclusive of the capital-cost charge) works out at 0.184¢ per ton-mile. The cost of slurry preparation and de-watering is not included.

TABLE 6

Coal Pipeline Costs, U.S.A. (ca 1962) - Investment and Operating

<u>Investment</u>	<u>\$ million</u>	<u>Operating Cost</u>	<u>¢ per ton</u>
Pipe installation, right-of-way, communications	4.1	Operating labour	1.7
Pipe line	5.3	Maintenance labour	2.1
Pump stations	4.6	Maintenance supplies	5.0
Tankage	0.3	Power	17.0
Contingency and interest	1.2	Chemicals	7.0
		Supervision, administration, general overhead, misc.,	4.0
	\$15.5 mill.		36.8
		Capital cost at 15%	77.5
		Total	114.3¢
		(0.572¢ per ton-mile)	

Table 7 refers to the same coal slurry pipeline but includes operating costs, slurry preparation and de-watering costs, and a 15% capital charge (295).

TABLE 7

Coal Pipeline Costs, U.S.A. (ca 1962) - Overall Transport Costs

Miles:	100	200	300	400	500
<u>Metric tons per year</u>	<u>Costs, ¢ per ton-mile</u>				
2 million	1.72	1.25	1.09	1.01	0.96
3 million	1.43	1.00	0.83	0.79	0.74
4 million	1.27	0.87	0.74	0.67	0.63
5 million	1.15	0.78	0.65	0.59	0.55
6 million	1.04	0.69	0.57	0.52	0.48

The element chargeable to slurry preparation, de-watering and 15% capital charge is given as 35¢ to 55¢ per ton and for 3.0 million tons is stated to be about 45¢ per ton. Figure 4 is adapted from Table 7 and shows the variation of total slurry pipelining costs versus line length and annual throughput.

4. In South Africa, coal is transported by a 9-in.-diameter pipe from the Doornfontein Colliery to the Komati Power Station (101, 177, 246), a distance of 1½ miles. The same water is used to return fly ash to the mine by 12-in. pipeline where the ash is used as hydraulic fill underground. The coal is of -1 in. size and the rate of pumping is about 120 tons per hour for 10 hours per day. Three 8-in. centrifugal pumps in series are used with 120-hp motors, rated at 1300 gpm each, handling coal and water at 30-35% concentration by weight. Some running costs are given (246), based on 300,000 tons per annum (Table 8). The costs apparently include a small amount of coal transported by road and/or rail. The capital cost (including cost of a 12-in. fly-ash line and a de-watering plant) is given as Rand 150,000 (U.S. \$210,000; 1 Rand = \$1.40 U.S.).

TABLE 8

Coal Pipeline Costs, S. Africa

	U.S. \$ per ton	U.S. \$ per ton-mile
Capital charges (10% per annum)	0.0630	0.0420
Power charges (0.28¢ per kwh)	0.0070	0.0046
Operation, maintenance, development	0.0350	0.0233
Loss (from coal not recovered)	<u>0.0140</u>	<u>0.0094</u>
	0.1190	0.0793

Gilsonite

The following statistics (202) (circa 1962) refer to the gilsonite pipeline of the American Gilsonite Company, which operates a 72-mile, 6-in. line. The line rises from about 5,740 ft to a maximum elevation of 8,430 ft, delivering to the refinery at 4,485 ft. A truck route would have entailed a haul of 200 miles (124). Relative to trucking, a saving of over \$4 per ton in over-all direct operating cost has been realized, amounting to about \$1 million per year and justifying the \$2 million capital required.

Costs of truck and pipeline in terms of cents per ton-mile were similar for both systems. Concentrations up to 40% by weight are pumped (1,200 tons solids per day). The feed size is -8 mesh and the minimum safe velocity was determined to be 3.4 ft/sec.

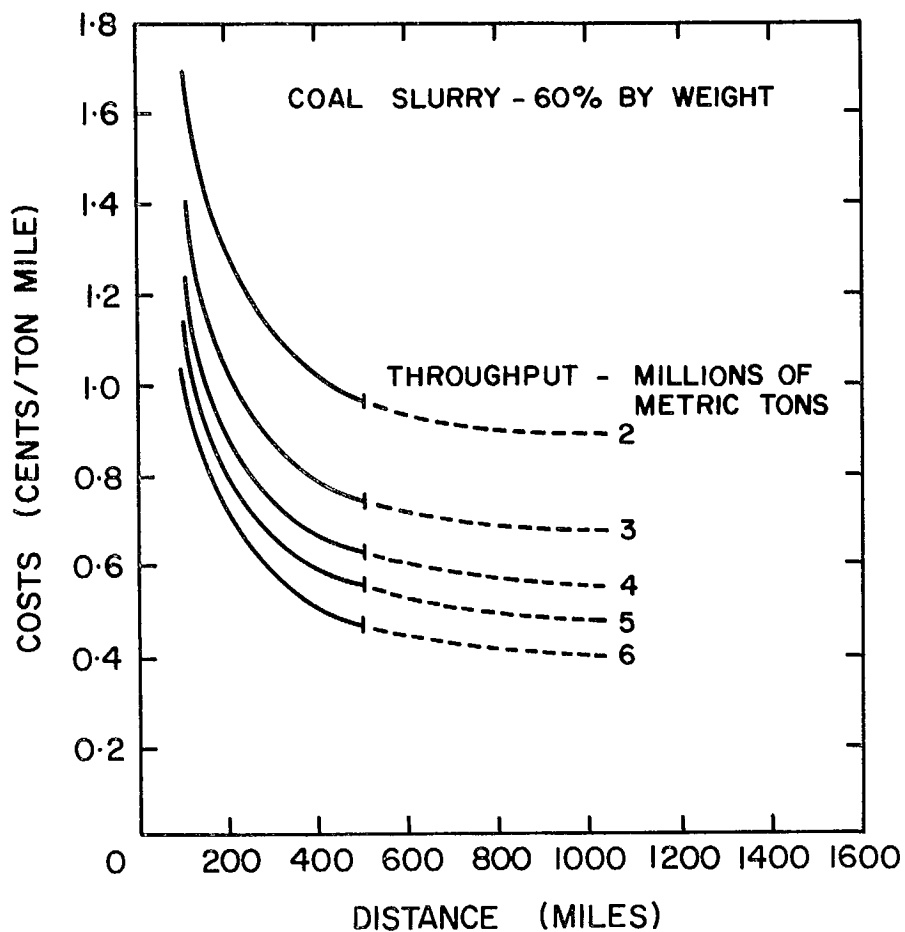


Figure 4. Total cost of transporting coal slurry. (See bibl. refs. 23, 295.)

Note: Costs = operating costs + capital charges at 15% of investment + preparation costs + dewatering costs.

Table 9 shows operating expenses (excluding depreciation and prorated general administration costs) based on 1,100 tons per day. De-watering has been credited with the value of water supplied to the refinery. Slurry preparation entails screening, crushing, desanding, and mixing to the required concentration with water.

TABLE 9

Gilsonite Pipeline Operating Costs, U.S.A. (ca 1962)

	Cost/ton \$	Cost/ton-mile \$
1. Not proportional to distance		
Slurry preparation	0.297	0.004
De-watering at refinery	<u>0.217</u>	<u>0.003</u>
	0.514	0.007
2. Proportional to distance		
Pump station	0.443	0.006
Pipeline	<u>0.040</u>	<u>0.001</u>
	0.483	0.007
Total	\$0.997	\$0.014

Uranium-bearing Slimes

With the advent of demand for uranium in the early 1950's, a number of extraction plants were set up on the Rand, in South Africa, to re-treat slimes from which the gold had previously been extracted. To deliver the slimes to central treatment plants, pipeline systems were established. One of the largest systems (242) is that in the Welkom area of the Orange Free State where two extraction plants are linked up to 6 mines through 25.8 miles of pipeline varying in size from 9- to 16-in. diameter, the latter delivering the equivalent of 120,000 dry tons per month. Data relating to that portion of the system using 12-in. and 16-in. line are given in Table 10. Slimes transported are, in general, not more than 5% +300 micron nor less than 50% -75 micron. Another system described (47) is in the Klerksdorp area of the Western Transvaal, where a total of four mines deliver slimes to two central collecting points for transport to the uranium extraction plant. This system uses pipe of 6-in. and 9-in. diameter, and relevant data are given in Tables 10 and 11. It should be noted that, in each of the two cases considered (Welkom and Klerksdorp areas), the larger line carries slime delivered by the smaller line plus an additional load of slime delivered at the junction of the larger and smaller lines. Pumps are sited at the intake of each line and are connected in series. No booster or lift pumps are used at intervals along the line, as is the practice in the Florida phosphate fields.

Costs for other South African slimes-carrying pipelines are given as ranging from \$0.0032 per ton-mile to \$0.0275 (349).

TABLE 10
Slimes Pipeline Data and Costs, S. Africa

	WELKOM AREA (pre-1961)		KLERKSDORP AREA (1956)	
	Freddies N. to Freddies S.	Freddies S. to Welkom Δ	Babrasco to Ellaton	Ellaton to Stillfontein Δ
Route (ft)	26,700	36,500	62,334	50,057
Route (miles)	5	7	11.81	9.48
Pipe size (in.)	12	16	6	9
Pipe thickness (in.)	0.1875	0.1875	0.176 and 0.212	0.1875 and 0.25
Average velocity (fps)	3.78	3.96	3.19	3.37
Designed capacity (dry tons per month)	176,000	249,000	37,000	88,000
Delivery (dry tons per month)	60,000	120,000	37,298	90,756
Running time (%)	34	48	Full	Full
Slurry, sp gr	1.46	1.46	1.46	1.46
Solids by weight (%)	50	50	50	50
Pipeline	Buried	Buried	Surface	Surface
Static head (linear ft)	+88	+136	-279	+101
Static and estimated fric- tion head (equiv. ft water)	380	467	519	700
Working pressure (psi)		260	225	304
Pumps used:	Three 8-in. rubber-lined centrifugals in series	Three 8-in. rubber-lined centrifugals in series	Two 6-plunger pumps in series, 5-in. dia x 7- in. stroke. (One is standby.)	* Four 6-plunger pumps in series, 5 in. dia x 7- in. stroke. Two 3-plunger pumps in series, 7 in.-dia x 18 in. stroke (3 are standby).
Motor hp (each pump)	150	150	200	120 and 160
Capital cost	\$229,600	\$380,800	\$1,335,000	
Capital cost per in. ² /mile	\$406	\$271	\$1,424	
Pumping cost per ton del'd	\$0.061		\$0.286	
Pumping cost per ton-mile	\$0.0064		\$0.020	

(Over)

Notes from Table 10

△ In the case of the first two mines above, the uranium extraction plant is sited at Welkom Gold Mining Company and in the case of the other two, at Stillfontein Gold Mining Company.

* The plunger pumps on the leg Ellaton to Stillfontein were later replaced by five 4-in. rubber-lined centrifugals in series in order to lower operating costs (108), the main reduction being in the cost of stores. There has been a progressive increase in pressure in this line and in the Babrasco-Ellaton line since startup and this is probably due to corrosion. The figures quoted recently are given below and these may be compared with the earlier figures in Table 10.

	<u>Ellaton - Stillfontein</u>	<u>Babrasco - Ellaton</u>
Pulp, sg	1.443	1.449
Pressure, psi	515	328
Velocity, fps	3.84	3.45

TABLE 11

Slimes-Pipeline Costs, S. Africa
(Monthly costs for 9-month period, 1956)

Item	Mine	Cost (\$)	Tons per month	Miles	Ton-miles	\$ per ton	\$ per ton-mile
Pumping costs	Babrasco to Ellaton	12,104	37,298	11.81	440,492	0.324	0.027
Pumping costs	Ellaton to Stillfontein	<u>14,073</u>	90,756	9.48	<u>860,362</u>	0.155	0.016
Pumping costs	Babrasco to Stillfontein	26,177			1,300,854		0.020
Thickening, filtering, and miscellaneous	At Stillfontein Plant	<u>7,924</u>			1,300,854		0.006
		34,101			1,300,854		0.026
Pumping costs, filtering, thickening, and miscellaneous:	Babrasco-Ellaton-Stillfontein						
(1) Salaries and wages		6,017			1,300,854		0.005
(2) Stores		15,723			1,300,854		0.012
(3) Power		2,248			1,300,854		0.002
(4) Workshop		4,474			1,300,854		0.003
(5) Other		<u>5,639</u>			1,300,854		<u>0.004</u>
		34,101					0.026
Per ton delivered	Stillfontein plant	34,101	90,756			0.376	-
Capital cost		1,334,998				\$0.085 per annual ton-mile	

Rock Phosphates (Florida)

1. Costs are generally confidential, due to the competitive nature of the business and to the number of different companies engaged therein. The following (Tables 12, 13, 14) are said to be generalized costs, circa 1957 (143). For the purpose of this calculation the following figures are assumed. The water pipeline is 1 mile long and all pump equipment and water line are written off over 10 years. The matrix is carried in a 16-in.-diameter pipeline handling 600 short tons per hour over 6,000 hours per annum (3.6 million tons per annum). The length of slurry pipeline is 2 miles with one pump station per mile (i.e., a total of 2 stations). This seems a rather longer interval than those described in more recent literature (290), where distances between stations vary from 1,800 to 3,200 ft. The slurry line is deemed to handle 8 million tons of matrix before requiring replacement (at 3.6 million tons the line would require replacement in 2.2 years - say 2 years for purpose of calculation). Power costs are 1 cent per horsepower-hour. 800 hp is required for pumping hydraulic water. The capital cost of the slurry pipeline is \$40,000 per mile, or \$20,000 per mile per year. Table 14 is a summary of the data derived from Tables 12 and 13 and shows an overall cost of 3.47 cents per ton-mile.

TABLE 12

(a) Phosphates - Slurry Preparation Costs, U. S. A.

Cost of water pumps, sump, motors, switches	\$ 40,000
Cost of 1 mile of 24-in. water line installed	40,000
Cost of hydraulic giant set-up	15,000
Cost of incidentals	<u>5,000</u>
Capital costs, total	100,000
Capital costs, total (per year)	10,000
Cost of maintenance, per year	\$ 5,000
Power costs	48,000
Other labour costs at \$5.50 per hour	<u>33,000</u>
Total per year	\$ 86,000

TABLE 13

(b) Phosphates - Slurry Transport Costs, U. S. A.

Cost of two 14-in. dredge-type pumps with motors, switch gear, etc., \$45-\$50,000 each say per year	\$10,000
Cost of maintenance and repairs for one year, \$5-\$10,000 for each station say	14,000
Cost of labour at \$3 per hour	18,000
Cost of power at 1 ¢ per ton mile*	72,000

*Power costs were calculated for various deliveries and percentages of solids.
A rounded figure of 1¢ per ton-mile was derived from the following table:

Gpm of slurry	6000	7000	6000	7000
Tons per hr of solids	600	600	784	914
Velocity (fps)	10.5	12.3	10.5	12.3
% solids by weight	32.4	28.5	40.0	40.0
hp-hour per ton-mile	0.78	1.18	0.63	0.84
Cost per ton-mile	\$0.0078	\$0.0118	\$0.0063	\$0.0084

TABLE 14

Phosphates - Slurry Pipeline Costs, U. S. A.

(Summary of Tables 12 and 13)

(a) Preparation:	<u>Per ton</u>	<u>Per ton-mile</u>
Capital Cost	\$0.0027	\$0.0014
Maintenance	0.0014	0.0007
Labour	0.0092	0.0046
Power	<u>0.0133</u>	<u>0.0067</u>
	0.0266	0.0134
(b) Transport:		
Capital Cost	0.0027	0.0014
Maintenance	0.0039	0.0019
Labour	0.0050	0.0025
Power	<u>0.0200</u>	<u>0.0100</u>
	0.0316	0.0158
(c) Pipeline:		
Capital Cost	0.0111	0.0055
Totals	0.0693	0.0347

With larger installations, it is believed, costs would be lower than the 6.9¢ per ton or 3.5¢ per ton-mile given in Table 14. Costs of transporting plant tailings are lower because the finer size of the material handled allows slurry pumps to be used and these can be designed to give higher efficiencies than the dredge-type of pump. A lower velocity, and hence lower power consumption, is also possible due to the fine sizes.

A further estimate of direct costs, circa 1961, based on a hypothetical line is available (120) (Table 15). In this case, a 16-in. line, 2.81 miles in length, carries 8,000 U.S. gpm at 35% solids by weight or 895 short tons of solids per hour. The slurry has a sp gr of 1.282 and the solids a sp gr of 2.7 dry. There are 3 pumps: a pit pump, and 2 booster pumps situated along the line. The 3 pumps require a total of 1,665 hhp. The power required to supply water to the giants is 0.89 hp per short ton. Power costs are based on 1.1¢ per kwh. Overall efficiency of the electric motors is 85%. Maintenance cost of the pumping units average \$1.50 per hour, and the pipeline is assumed to have a life of 6.7 million short tons.

TABLE 15

Phosphate - Slurry Transport Costs (USA) (ca 1961)

	Per ton	Per ton-mile
Cost of power, pumping slurry	\$0.0202	\$0.0072
Cost of power, pumping water	0.0093	0.0033
Cost of labor	0.0185	0.0066
Cost of maintenance	<u>0.0062</u>	<u>0.0022</u>
Sub-total	0.0542	0.0193
Cost of pipeline replacement	0.0208	0.0074
Cost of interest	<u>0.0054</u>	<u>0.0019</u>
Sub-total	0.0262	0.0093
Grand total	0.0804	0.0286

Iron Ore Concentrates

Detailed studies have been made of the transport of a magnetite slurry from the Mesabi Range to markets in Chicago (67). The 500-mile pipeline would require an investment of \$70 million, and total transportation costs (including all variable and fixed costs with amortization over 15 years) are estimated at about \$17.5 million per year. This is equivalent to \$1.75 per ton, or 0.35¢ per ton-mile.

A 250-mile line to move iron-ore concentrates from Minas Gerais, Brazil, to Rio de Janeiro is under study. Costs would be approximately \$23 million and the line would move 4 million tons per year at \$2 per ton or 0.8¢ per ton-mile.

The Colorado School of Mines Research Foundation, in its book, "The Transportation of Solids in Steel Pipes" (349), has reviewed all aspects of solids transport up to 1963. The section headed "Summary of Theories of Pipeline Transport of Solids" reviews the more important experimental work carried out and presents 16 equations applicable to the solving of pipeline transport problems. Chapter 4, "Application of Theoretical Formulas for Solids Pipeline Studies", applies certain of the formulas given to three hypothetical transport problems involving coal, limestone, and taconite. The taconite problem is worked for three different mineral sizes, 1 in., 1/8 in., and 100 mesh. The ore is to be transported over a distance of 25 miles at a rate of 4 million dry tons per year at 50% solids and has a sp gr of 3.2, the slurry having a sp gr of 1.52. The following are the theoretical results:

TABLE 16

Pipeline Velocities for Iron-Ore Transport

Size of Product	Friction head loss for 25 miles of line (ft of water)	Chosen pipe dia. (in.)	Critical velocity (fps)	Transport velocity (fps)	Transition velocity (fps)
1 in.	43,824	8	13.10	15.34	14.45 (a)
1/8 in.	15,100	8	9.70	15.34	15.68 (b)
100 mesh	6,019	10	5.43	9.73	7.28 (b)

(a) Transition from heterogeneous flow to flow by saltation.

(b) Transition from homogeneous flow to heterogeneous flow.

III. PRACTICE IN THE FLORIDA PHOSPHATE FIELDS

(36, 92, 97, 120, 143, 222, 285, 286, 290)

The date when phosphate mining in Florida started is given variously as in the 1860's and as 1888. It is stated that by about 1900, solids-handling pumps were in use. The phosphate-rock ore (generally known as matrix) occurs in beds up to 35 ft thick covered by 10 to 50 ft of overburden. The beds contain, in addition to the phosphate rock, unconsolidated clay and silica sand of -1 mm size. The matrix as mined weighs 120 lb per cubic foot and contains 20% moisture. In 1967 Florida produced 26 million tons of rock phosphate. In general, for each ton of phosphate-rock produced it is necessary to pump 3 tons of matrix to the recovery plants and dispose of 2 tons of sand tailings and slimes as waste. This gives a figure of approximately 78 million tons being transported annually in the mining and waste disposal processes. Water consumption for all purposes is about 10,000 to 12,000 gpm per ton of rock produced and 75% of the water used is recovered.

Mining is by drag line, the overburden being stripped and the ore mined and dumped into a sump where it is broken up by a battery of hydraulic giants. The giants operate at pressures of 100 to 250 lb psi and are remotely controlled. The slurry, at 30 to 40% solids by weight, is then picked up by the centrifugal pit-pump and delivered to the washing plant, which may be at a distance of some miles. Booster pumps are situated at intervals along the line. The washing plant produces clean rock-phosphate of about +14 mesh, a -150 mesh slime, and a flotation feed. The flotation plant produces a clean phosphate and further tailings products which are piped and pumped to waste, the water being recovered for further use.

The size of equipment used over the years has tended to increase, and pit-pumps to handle slurry may be up to 18-in. and slurry lines to 20-in. diameter. The hydraulic giants may each deliver 3,000 gpm. The slurry passes through a grizzly before reaching the pit-pump suction and grizzly bars may be spaced 4 in. to 8 in. apart. A typical layout may have an 18 in. x 48½ in. centrifugal dredge-type slurry pump with 24-in. suction driven by a 1,250-hp electric motor with variable speed control. 18,000 gpm would be handled with a solids content of 35 to 40% (2600 dry tons per hr). Three giants would be sled-mounted operating at 200 psi and supplied with 10,000 gpm of clean water. The water pump would be 18 in. x 24 in. with a 900-hp motor capable of delivering 10,000 gpm at 300 ft head, and the grizzly would be of 6 in. spacing. Booster pumps for the slurry would be set at intervals of 3,000 ft, and there would be booster pumps in series at intervals in the water line.

The suction lines of the slurry pumps may have bell mouths on the intakes to reduce entrance-head losses. Pumps and motors are sled-mounted, and various types of special devices are used to prevent damage from water hammer. The suction lines can be raised or lowered by an electric winch to control the density of the slurry being pumped. All pumps handling slurry are remotely controlled by a push-button system at the mine sump. This system ensures that the proper speed and run-up sequence is maintained. A flow meter is used to determine gpm being pumped; a density meter records % solids and an integrator converts this information into dry tons per hour.

Pipe lines may be of spiral-weld steel pipe of special composition. C.I. pipe of nodular iron with 1/4-in. walls may be used. Joints are flanged, as long welded lines are troublesome when blockages occur. Blockages may be dealt with by pumping clear water through the line, or finding the blockage by sounding and removing the plugged pipe. When pumping down grades greater than 2%, humps are introduced into the line to prevent the liquid's flowing away from the solids and causing a stoppage. Relief valves at the top of the humps prevent syphoning during shutdowns and loss of prime-water. No difficulty is met in pumping up moderate grades, or in vertical pumping.

Pipe wear is checked with an ultrasonic thickness gauge. Most wear takes place in the bottom 120° segment of the pipeline and the line is rotated through a 120° arc after handling a set tonnage. Some mines rotate their lines through 90°. Piping used within the concentrating plants is neoprene-lined. The life of a slurry line may be 6 million tons or more; a life of +8 million cu yds is mentioned, and pipes are turned through 120° after every 2½ million cu yds.

The velocity in the slurry line varies from 10 to 18 fps, the higher velocities being required for slurries containing a higher proportion of coarse material. A high slime content is said to improve the "pumpability" of the ore or matrix slurry. (In this connection, see Figure 5 where the "pumpability" of coal is improved by the addition of fines.) The siting of booster stations in the slurry line is controlled by the length of line, the velocity of the slurry, and the configuration of the terrain. The more usual intervals are between 1,500 and 3,500 feet. The slurry generally travels directly from pump to pump; one mine, however, delivers to open sumps before the booster pumps.

The disposal of waste products accounts for a substantial part of the rock-phosphate production costs. The two waste products are the -150 mesh slimes and the silica sand. The slimes are in a slurry of 3 to 5% solids with a volume of perhaps 40,000 to 50,000 gpm. Flow may be by gravity or by vertical centrifugal pump, or both, to settling areas. The silica sand may be pumped for several miles; pumps used are volute-type, fully neoprene-lined. A 16-in. pump could handle 700 tons per hour of tailing in a 35% slurry (7,500 to 10,000 gpm at 15 fps) and would require a 600-hp motor.

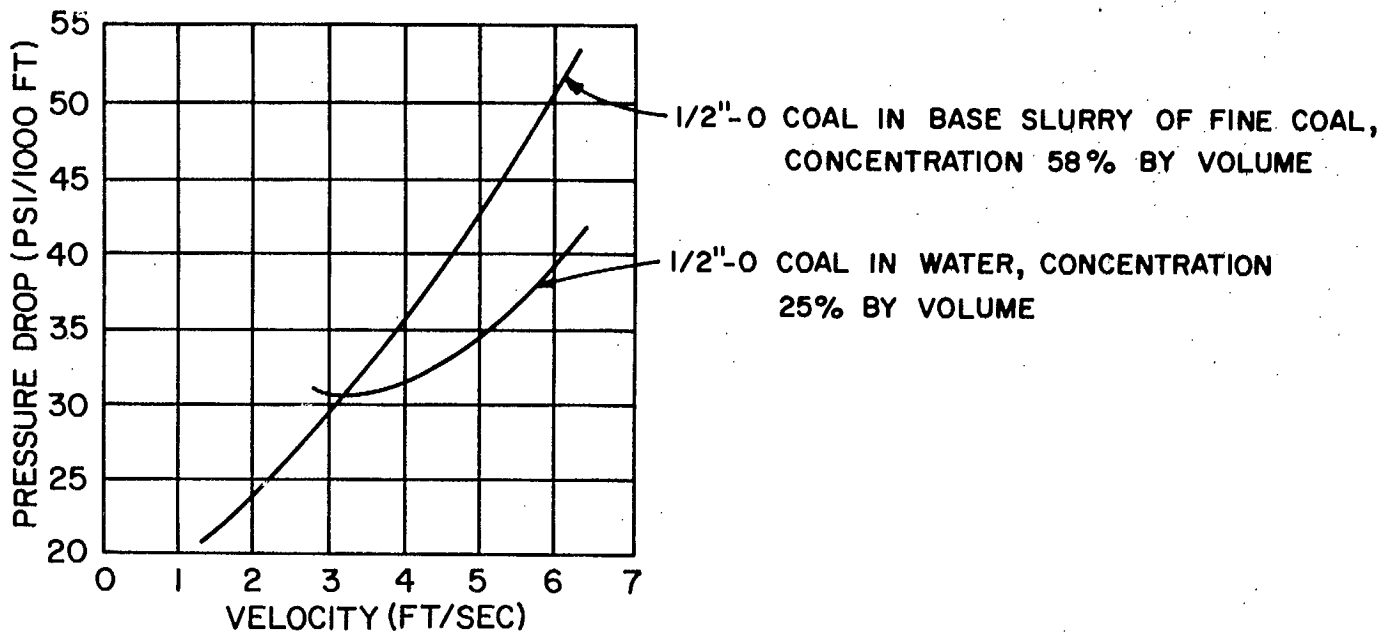


Figure 5. Extension of regime of stable operation by addition of fine material to coal-slurry in 2-in. pipe. (See bibl. ref. 33.)

IV. VERTICAL TRANSPORT AND FEEDERS

While hydraulic hoisting of coal is used in a number of countries, the only known hydraulic hoisting of mineral ores is at Bancroft Mine, Zambia. Where a mine has, as a matter of necessity, to pump considerable quantities of waste water to surface, it would seem logical to consider the possibility of continuous hydraulic hoisting to replace, or partly replace, intermittent conventional hoisting. Some crushing underground would be required. The hoisting experiments at Calumet and Hecla (105) were successful in hoisting ore to 4-in. size, and some pieces much larger reached surface. Problems of developing a feeder and of wear in pipes may present difficulties. A perusal of the literature does not indicate exactly why this method of hoisting has not received wider attention, nor why experimental installations were not developed for full-scale operation.

Pressure-drop is of vital importance in vertical hydraulic transport, as it is the main energy consumer in the balanced leg system (one downcast and one upcast pipe), and most experimental work has been carried out to determine pressure-drop under various conditions. Newitt (211) in 1961 carried out experiments using various materials, including pebbles, to 0.15-in. diameter in pipes of 1-in. and 2-in. diameter at velocities to 10 fps and to 35% concentration by volume. He found that slurries composed of large particles (+.01 in.) having terminal fall-velocities in the transition and turbulent flow regions gave frictional pressure-drops very similar to water friction-drop pressures. Flash photos showed that while these particles were randomly distributed at low velocities, they tended to move towards the pipe centre at high velocity, leaving an annulus of almost clear water. This effect explains the similarity in pressure-drops previously mentioned. However, slurries of fine particles (-.01 in.) with low terminal falling-velocities gave pressure-drop curves which tended to diverge from the corresponding water friction curves as the velocity increased.

Earlier experimenters were Worster and Denny (323), who in 1955 conveyed coal and gravel in 3-, 4- and 6-in. pipes, both vertical and horizontal. The coal was up to 1 in. in size and the gravel to 3/16 in. Concentrations of coal to 20% by volume were used in the vertical tests. The various types of feeders as developed at that time are also described (lock hopper, double-acting reciprocal feeder, and disk feeder). Durand (1953) (90) also carried out experimental work on sands.

Kostiuk in Canada (1961) (166, 167, 168) used crushed magnetite in his work. The magnetite was in sizes 97% -3 mesh with a sp gr of 4.08 in 2-in. pipe at concentrations to 20% by volume and velocities of 7 to 15 fps. This experimenter found that friction loss in the vertical pipe was equal to the friction loss of water at the same velocity, provided the ratio, mean mixture velocity divided by weighted mean terminal fall velocity, was greater than 10; that is, the delivered volumetric concentration was approximately the same as the spatial volumetric concentration. He also states that the minimum velocity for vertical transport is $1\frac{1}{2}$ times the unhindered terminal fall velocity of the largest particle in a given size range.

The same author examined hydraulic hoisting versus conventional double-drum cylindrical hoisting and considered the former to be most attractive from the economic point of view. The highest hoisting efficiencies and lowest power requirements resulted from the highest possible concentration and the smallest practicable particle diameter.

More recent work by Oedjoe (217), in 1966, entailed the use of a patented feeding system, known as a "Hydrolift" (42, 352), which enabled him to obtain higher solid concentrations (45% by volume) and to use a larger size of solids than previous workers. Coal to 3 in. and gravel to 3/4 in. were used in pipes to 4-in. diameter and velocities to 5 fps. It was found that the pressure-drop equations developed by Newitt and others applied fairly closely to dense slurries of large solids with wide size distribution when the free settling velocity of the weight-average particle size is employed.

The "Hydrolift" (42, 352, 367a) has been developed at the University of New South Wales, Australia. Material is lifted by a jet working inside a pressurized feed vessel. Feed control of the solid-liquid ratio is obtained by moving the delivery pipe up or down in relation to its position over the jet, or, alternatively, by moving a hydraulically controlled sleeve on the end of the lift pipe. The water pump handles only clean water, and a balanced leg system may be used. It is claimed that material to 24-in. diameter can be handled and that a 24-in.-diameter line could handle 1,000 tons per hour. Recent experimental work has been with gravel up to 1/2 in. and coal to 3 in. size. Velocity in the Hydro-lift is low and concentrations to 60% by volume are possible. It is now being tested in South Africa.

Cloete (57) in 1967 studied dense phase flows of sands and glass ballotini of size -.0275 in. in 1/2-in. and 3/4-in. pipes at velocities to 10 fps and with concentrations of over 50% by volume. Dense-phase flows are defined as being obtained when the solids fraction in the pipe is of the same order as the solids fraction of a freely settled bed of the solids in the fluid, and for these conditions the author found that the pressure-drop correlation derived by Oedjoe did not apply.

Zandi and Govatos (328) have recently (1967) collected together all data for heterogeneous flow of solids in pipelines and subjected this information to computer analysis. They came to the conclusion that head losses were well predicted by the equations of Durand, Condolios and Newitt (210, 211) once saltation data had been removed. Worster's (322, 323) equations were found to be invalid. A set of two equations of the Durand type is proposed by these authors and predictions are found to be superior to all others. It is also stated that flow phenomena between heterogeneous and saltation regimes are complex and require further study.

Vertical hydraulic transport of coal from underground to surface has been used successfully in a number of countries, and various types of feeders have been developed. The only known use of vertical transport for mineral ore is at the Bancroft Mine in Zambia. Elsewhere, ore has been hoisted experimentally. Hydraulic elevators -- venturi-type devices using high-pressure water at the nozzles -- are still used in certain alluvial mining operations. However, their efficiency is low and the height of lift is controlled by the water pressure available at the nozzle. Venturi devices and nozzles combined with air-lift are finding increasing application for under-water dredging

and under-water sampling.

The United States Bureau of Mines developed, in 1965, a lock hopper feed system (80) for the hydraulic hoisting of coal. Coal up to 3-in. size was hoisted vertically in a 6-in. pipeline at a velocity of 9 fps. The Westerfield open-cast coal mine (368), the largest in the U.K., transports a $-\frac{1}{2}$ mm slurry to waste through 3,000 ft of 3-in. pipe. A lock-hopper system developed by International Combustion Products Ltd. is used. This system has 2 lock hoppers, a high-pressure, 9-stage centrifugal pump handling clear water only, a low-pressure slurry pump drawing slurry into the hoppers, and a second low-pressure pump to handle dirty water from the hoppers. Plug valves to the hoppers are electrically controlled and pneumatically operated. Working pressure in the line is about 250 psi, with solids up to 55% by weight. This system has, in practice, proved most economical and successful, and synchronous timers ensure there is no interruption of slurry flow from the pressurized hoppers. Although the system is essentially one of horizontal flow, there is no reason why it could not be applied to vertical transport.

At the Debiensko Colliery in Poland (34, 308), $-1\frac{1}{2}$ -in. coal is pumped through pipelines for 3 miles underground at the rate of 100 tons per hour and then pumped vertically through 1,050 ft to surface.

Hydraulic transport and vertical lift are quite widely used in USSR coal mines (333, 382). In some installations a spiral helical screw of constant pitch (373) is used to force coal into the pressurized line. One of the lock-hopper systems incorporates a compensating plunger whose purpose is to obviate the necessity of discharging a volume of water from the upper hopper equal to the volume of feed introduced. This system is used to lift 60 tons per hour of abrasive rock through 1,300 ft. Rock to $2\frac{1}{2}$ in. is lifted at speeds of 9.2 to 9.8 fps; the pipe diameter is 6 in. Chinese coal mines use centrifugal pumps to hoist 2-in. coal at the rate of 80 to 150 tons per hour through 1,477 ft (56). A system using a chamber-feeder on the water-exchange principle has been installed to lift through 1,827 ft at the rate of 57 tons per hour. The Sunagwa Coal Mine, in Japan, pumps 100 tons per hour through 1,700 vertical feet of $7\frac{1}{2}$ -in. internal diameter pipeline.

The Yoshima Mine of the Furakwa Mining Company Ltd. in Japan (280) uses a "Hitachi Hydrohoist" to lift coal through 853 ft vertical at 100 tons per hour. This hoist has been in use since 1961. The coal is -2 in. size. In this system there are 5 feeder compartments about 165 feet in length and of about the same diameter as the conveying pipes. A "bladeless sand pump" delivers a coal-water mixture into one feeder tube and this is ejected and moved up the conveying pipe by water from a high-pressure turbine pump. The same feeding and ejection process is carried out in sequence, using all 5 feeders and a system of valves. The valves are not described.

In France a great deal of effort has been devoted to hydraulic hoisting of coal (51, 72, 74), and extensive test and research programmes carried out by Sogreah. A hydraulic hoisting installation has been operating at the Devillaine mine near St. Etienne since 1960. Coal up to $3\frac{1}{4}$ in. in size is lifted through 590 ft at the rate of 50 to 60 tons per hour, with an energy requirement of 48 hp. The main pump is situated on the surface and a system of two lock-hoppers is used. Very fine coal ($-.04$ in.), being difficult

to settle out, remains in the circuit and this, in fact, facilitates transport of the coarser coal. Based on information obtained at St. Etienne (c. 1963), the following estimates are given for hoisting -1 1/4 in. copper ore at 300 tons per hour through 2,600 ft with the cost of power being 1¢ per kwh:

Power, 3.3 kw per ton	-	\$0.0329 per ton hoisted
Labour, \$7,000 per man-year	-	0.0171 per ton hoisted
Plant maintenance	-	<u>0.0110</u> per ton hoisted
Total operating costs	-	0.0610 per ton hoisted

\$0.12 per ton-mile.

The 72-mile gilsonite line in the U.S.A. (202, 276) has been mentioned previously. This mine also uses vertical transport. The ore is broken by hydraulic jets at 2,000 lb psi and gravitates to a sump where a 6-in. vertical submerged pump delivers the slurry to six 6-in. centrifugal pumps which move the slurry through 850 feet vertical distance to the surface and a further 1,200 ft horizontally on surface to the preparation plant, where the ore is prepared for long-distance hydraulic transport. Pump motors are of 300 hp each.

The prepared slurry has +95% of -8 mesh size and a maximum particle size of 4 mesh. Pumping is at the rate of 1,200 tons per day, or 405 gpm, with a slurry concentration of 48% by weight. This is a maximum tonnage due to pipeline pressure-limit of 2,600 lb psi at the pump station. Increased throughput would require a booster station. The 1,200 tons per day represents an increase of 71% on designed capacity, so that in practice the line has been considerably more effective than design limits had indicated. The gilsonite has a density of only 1.04 (coal 1.34 to 1.55).

Bancroft Mines Ltd. (8, 63, 231) operates a copper mine in Zambia and a hydraulic ore-lift has been in operation there since about 1960. The mine was planned to handle ore with a moisture content of 10%; however, when stoping commenced it became apparent that the ore was not only very wet in situ but furthermore it broke down readily into a slurry which presented very difficult control problems in ore passes, in feeder chutes and on belt conveyors. The system finally adopted was to wash and screen all ore underground after first crushing to -6 in. The oversize material from screening and washing (+3/16 in.) is handled by conventional hoisting but the remaining 32% by weight is handled by pumps as a slurry. There are 2 banks of rubber-lined centrifugal pumps, 8 in. x 8 in.; each bank consists of 9 pumps in series with 80-hp motors each. One bank is situated on the 1,317-ft level and one on the 650-ft level; the lower bank delivers to an open sump on the 650-ft level. The pumps are designed to operate against 1,500 ft head, so that the lower bank could, if necessary, pump directly to the surface. Special controls are used to maintain the correct pressure at the glands. The pipeline is of 8 in. diameter and carries 1,000 gpm at a maximum density of 1.5, giving a concentration by weight of 60% and a velocity of 7.2 fps.

At Mufulira Mine (188), also in Zambia, sludge is transported vertically to the surface through 1,430 ft. In this system, a reciprocating pump at the surface circulates clean water through a double-leg, 4-in. pipeline system. The sludge is delivered in batches from cones to a rock chamber in the mine bottom, the chamber being sealed with a reinforced concrete plug. A compressed-air line leads into the top of the chamber, the air being used to force out dirty water to the drains. By operating a series of appropriate valves, the chamber is intermittently filled with sludge, the sludge pumped to surface, the dirty water in chamber forced to drains by compressed air, and the filling cycle started again. A nozzle is incorporated in the rising pipe line within the chamber to handle the sludge. An integral part of this system is an orifice across the two pipe-mains which ensures proper and controlled dilution of the sludge being pumped in the rising main. In the same mine a system of batch injection of the sludge directly into a 16-in.-diameter rising water-main is also used.

The National Coal Board (UK) has carried out considerable work on hydraulic transport at Markham and Woodend Collieries (184, 308, 341, 347). Various types of feeders were constructed and tested. These have been of 2 types: (a) low-capacity, high-speed feeding, and (b) high-capacity, low-speed feeding. Of the first type, a rotary valve feeder and a reciprocating feeder using a piston were tested. The high-capacity type included various types of lockhoppers -- vertical and horizontal. A horizontal type developed was found satisfactory. This required a wet feed from a low-pressure, solids-handling pump with separate high-pressure water pump and a system of plug valves with integral compressed-air actuators.

The Mining Research Establishment of the Dutch State Mines (coal) carries out research and experimental work on hydraulic transport, including vertical transport and feeders (100) of various types.

Experimental hoisting was carried out at Cølumet and Hecla Consolidated Copper Company's mine (105) in Wisconsin in 1952. A lock hopper system was used to feed the ore into the rising main of 10-in. diameter. Five pumps delivering approximately 2,000 gpm water, derived from underground sumps, provided the hoisting medium. The ore was crushed underground to 4 in. and hoisted in batches at the rate of 120 tons per hour, through 365 feet vertical. It was stated that an increase of flow to 2,500 gpm would increase the tonnage hoisted to 240 tons per hour.

In 1964, experiments in vertical hoisting were carried out by Sherritt-Gordon Mines at their Lynn Lake property (366) in Manitoba. The ore was crushed to 3-in. size and pumped to surface through a 6-in. pipe at the rate of 70 tons per hour. Falconbridge Mines has recently carried out some experimental hydraulic hoisting.

At the Vaal Reefs South Mine, in South Africa, it is planned* to use four large-capacity, high-lift Mars pumps to stage-hoist ore through 7,200 ft to surface. These pumps will handle material up to 10-mesh size from under-

*Mng. Mag., Oct. 1969, p. 288.

ground crushers. Up to 18% of the shaft tonnage will be handled by this method. The International Nickel Company of Canada Ltd. plan to use Mars high-pressure pumps at their Thompson Mine to lift mine sludge. The lift will be approximately 2,000 ft.

Table 17 lists some of the vertical-hoist installations used in metal and coal mines. References are given to the source of information.

TABLE 17

Solids-Carrying Vertical-Hoist Pipeline Systems

Material	Mine	Size of Material	Velocity in Pipe	Pipe Size	Vert. Lift	% Conc. by Weight	Tons Hoisted	Pumps and Feeders	Solids (sp gr)	Status	Bib. Ref.
Coal	Furukawa Mining Co. (Yoshima Mine) Japan	-2"		6½"	853'	20% (by volume)	100 tons p hour	Hitachi hydro-hoist u/g with bladeless sand pump and h.p. centrifugal. Mine drainage water used	1.68	Operating 1961	280
Coal	Woodend Colliery (NCS), Scotland	2"		7"	250'		35 tons p hour	Crank-driven reciprocal feeder, h.p. turbine water-pump & centrifugal suction-feed pump. All u/g.		Experi-mental	184 341 346 347
Coal	Debiensko Mine, Poland	to 3"		10"	1050'		100 tons p hour	Centrifugal pump & feeder. Open flow		Operating	34, 246 308
Coal	Andaluzja Mine, Poland				1027'		120 tons p hour	"		Installed 1950	34 246
Coal	Radoszowa Mine, Poland				1804'			"		Installed 1951	34 246
Coal	Sunagwa Colliery, Japan	-1.2"		Horizontal 5600' of 6½" dia. - vertical 1700' of 7½" dia.		To 25% by vol.	100 tons p hour	Hitachi pump and feeder device.		Operating 1965	141 147 302
Coal	China				1827'		57 tons p hour	2 centrifugal pumps on surface; chamber-type feeders u/g		Operating	56
Coal	France	-4"			1650'		200 tons p hour			Design stage 1967	72
Gilsonite	American Gilsonite Co., Utah, U.S.A.				850' vertical 1200' horizontal		100 tons p hour	6 centrifugals			8 202 276

Coal & Schist	Déville Mine near St. Etienne, France	- 3 1/4"			590'		50-60 tons p hour	48-hp centrifugal on surface. Balanced leg. Lock-hoppers u/g.		Operating	9, 51, 72 74, 175,
	Dahlhauser Tiefbau Mine, Bochum, Germany	0.8"		2.4"	2362'	to 17%	8 tons p hour	Open circuit, water from u/g by hydraulic mining. 2 cylinder piston-type pump u/g	to 2.4	Operating 1965	246
Waste Rock	Yuzhnaya Colliery, U.S.S.R.	to 75 mm (3")	8.5 fps	6"	446'			4 feeder chambers used		Test installation 1960. Apparently unsatisfactory, high cost & low efficiency.	333
Mineral Ore	Belkina Mine, U.S.S.R.	-2 3/8"	9.2 to 9.8 fps	6"	1310'	24%	57 tons p hour	Pump on surface. Batch feeder u/g	2.6 to 3.2	Operating 1964	373 382
Mineral Ore	Lynn Lake Mine, Canada	3"		6"	200'		70 tons p hour			Experimental 1964	366
Mineral Ore	Bancroft Mine, S. Rhodesia	-1/4"	7.2 fps	8"	2 lifts 650' & 667'	60%	240 tons p hour	2 stations of 9 pumps each in series. Rubber-lined 8" x 8" centrifugals of 80 hp each	2.7		8 63 231
	Calumet & Hecla Mining Company, Wis., U.S.A.	-4" (some to 10" long)		10"	365'		120 tons p hour	Lock hopper & centrifugal pumps		Experimental 1952	105
Iron Ore	Lengede Mine of Ilsede Iron Works, Peine, W. Germany	-35 mm		8.8"	130 metres (427')	Ore/water 1:4 by volume	300 tons p hour, 5,200 tons p day	2500 gpm. Two single-stage centrifugal pumps in series.	3.3? (slurry sg 1.375)	Operating	World Mng. June '69
Gold Ore	Vaal Reefs South Mine, S. Africa	to 10 mesh		6"	7200'	35%	About 25,000 dry tons p month	4 Mars pumps, 500 hp each	2.7 (slurry sg 1.28)	Planned for 1970	Mng. Mag., Oct. '69

Mine Sludge	Mufulira Mine, Zambia	Fine Slimes	4"	1430'		Reciprocating pump on sur- face. Air-pressurized rock cavity sump u/g. Balanced leg operation	Operating from 1962	188
			4"	500' 1st stage	30 tons p day	Reciprocating pumps	Operating	188
			16" rising main	930' 2nd stage	do	3-throw geared ram-pump injects into main	"	188
			4"	various		Displacement systems using centrifugal pumps and steel cylinders	"	188
Sand Fill	Hecla Mining Company (Star & Morning Mines), Idaho, U.S.A.			to 1000'	55%	Reciprocating pump	Operating	19
Sand Fill	Calera Mining Company, Idaho U. S.A.		6"	7167' of line rising 977' verti- cal	45%	8 stations with 2 centri- fugal pumps each	Operating 1959	274
	Headon Clay Pit, U.K.		8"	inclined (vert.= 140')	12-13 tons p hour	Gravel pump in pit	Operating	365

V. DREDGING OPERATIONS

Dredging operations with floating suction-cutter dredges often entail handling large volumes of slurry over considerable distances. One large operation at present underway is at Inco's Pipe mine, in Manitoba, where a 1,200-ton dredge is used to strip 13 million cu yds of material with an average depth of 100 ft, the slurry travelling 14,000 ft in a 32-in.-diameter pipeline. A 24-in. portable suction-dredge is being used at the Griffith Mine, of Stelco, Bruce Lake, Ont., to strip two separate iron-ore bodies beneath the lake waters.

Steep Rock Lake, Ont., has been the scene of extensive suction-dredging operations to uncover iron-ore bodies in the lake, buried beneath silt and gravel, preparatory to open-pit mining. Slurry pipelining on a large scale was entailed in these projects and some of the material handled was up to boulder size. Steep Rock Iron Mines Ltd. (22) during the years 1950-1954 dredged 55.9 million cu yds from the 'Hogarth' (or 'A') ore-body, and, during 1956-61, 46.7 million cu yds from the 'G' ore-body. The same two dredges, equipped with 30- and 36-in. pumps, were used over both ore-bodies. A 16-in. suction-dredge was also used on the 'Errington' (or 'B') ore-body for stripping of silt, from about the year 1956. During operations over the Hogarth body, initial static head at pump was 150 ft and final head 400 ft. The slurry was pumped to a storage area at up to 20% solids through 4,000 ft of discharge line. Costs for the stripping operation (1951-54) are given as follows, based on 55,736,000 cu yds excavated:

Labour and supplies	\$0.0716 per cu yd; 0.048 per ton*
Power	0.0231 per cu yd; 0.015 per ton
Administration	<u>0.0069</u> per cu yd; <u>0.005</u> per ton
	0.1016 per cu yd; 0.068 per ton

* No figures of weight in situ are given--3,000 lb per cu yd has been used to give an approximate tonnage cost.

The Caland iron-ore body (223,248) in the same lake was stripped of 161.8 million cu yds of material up to 400 ft in thickness by two rotary cutter dredges which started operations in 1955 and finished 5½ years later. The two dredges were similar and each had a 36-in. suction line, the cutter being driven by a 1,000-hp motor and the 36-in.-diameter dredge pump by a similar motor. Each dredge pump delivered into separate lines--firstly into a 36-in. floating line up to 1 mile in length, followed by a floating 36-in. booster pump with a 10,000-hp motor and thence through 200 ft of 40-in. shore-based line to a second 36-in. booster pump with a 10,000-hp motor, and finally into 4.4 miles of 42-in. line which delivered the slurry into Marmon Lake storage area. In general, the slurry velocity was 10 to 21 fps, and solids by volume was 6½% to 21%. This would give a maximum of about 5,450 cu yds per hour per pipe line. More gravel than expected was encountered and the pumps handled a few boulders up to 20 in. diameter.

Suction dredging was also used by Lake Asbestos, of Quebec, to strip 27 million cu yds of material from an ore-body in Black Lake (350). The pontoon line was 3,300 ft in length and the land line 20,000 ft, both of 32-in. diameter. The dredge had a 32-in. pump driven by a 6,000-hp motor. There were two booster pumps on the shore line; one of 6,000 hp and one of 3,000 hp and velocity in the pipeline was 17 fps. The mine started production in 1958.

Another large-scale suction dredging project, started in 1929, was that of the Beauharnois Canal (192) on the Ottawa River, where 2 suction dredges were used. One dredge was built to handle boulder clay, and boulders to 30 in. could pass through the dredge pump. This dredge had a capacity of over 6 million cu yds per year. This project also made use of pipeline transportation to deliver rock crushed to 5 in. through 2,000 ft of pipeline at a rate of 120 tons per hour. An 18-in. pump driven by a 1,500-hp motor was used.

Air-lift dredging has recently been used in offshore diamond-winning operations on the coast of S.W. Africa. This method of lifting solids is also being used in new developments of tools for under-water sampling. By injecting air into a submerged pipe at about 60% of depth of submergence, the density of the fluid column inside the pipe can be lessened, forcing the fluid to rise in the pipeline and carry suspended solids upwards.

VI. PIPELINE WEAR

There is little published information on this subject, most of that known emanating from the USSR (40, 201, 289, 291, 292, 293). It is stated that when abrasive rocks are transported, pipeline wear may account for 40% to 50% of the total cost of transport. Tests on the abrasiveness of mill slurries (160) were carried out in Canada, using particle size to about 10 mesh. In the Florida phosphate fields the life of a pipeline is given as 6 to 8 million tons, the line being turned at intervals. (This, for the larger lines, would be a life of perhaps 1 to 1½ years.)

VII. DE-FLOCCULANTS FOR SLURRIES

Sodium tripolyphosphate and tetrasodium pyrophosphate are used as thinners in wet-process cement plants (55, 241, 306). The addition of these agents to the fine shale or limestone slurries handled in the cement plants allows the slurry water-content to be lowered and improves the pumpability of the slurry. The effect of the de-flocculant is to break up the agglomeration of particles in which water is trapped -- this entrapped water not in any way aiding the flow of the slurry. The amount of additives used is small -- 0.05 to 0.10 per cent.

VIII. FRICTION-REDUCING AGENTS

An interesting development is the possibility of using Polyox friction-reducing agents (252) in slurry lines. Laboratory tests showed that concentrations as low as 100 ppm doubled the flow capacity of pipes and hoses before turbulent flow began, by reducing frictional drag of solutions in which it is dissolved.

The experimental use of polyethylene oxide as a friction-reducing agent has reduced fuel consumption of a mine sweeper by 15%. In Dallas and Cleveland the use of similar chemicals in sewer lines has resulted in a 2.5-fold increase in flow.*

IX. RIFLED PIPES (52, 178, 228)

Some early work was carried out by G.W. Howard in about 1939 on the rifling of 4-in. pipes carrying solids (129). More recently (circa 1965), S.E. Wolfe of the University of Toronto (321) carried out studies on helically ribbed pipes and came to the conclusion that the ribs allowed much lower velocities to be used than would have been the case in smooth-bore pipes. The ribs should have a high angle in relation to the long axis of the pipe, and lineal spacing between ribs should be modest. The effect of the ribs is to return any settled solids to the main stream.

X. DEFINITIONS

At low concentrations, slurries exhibit Newtonian properties, whereas at higher concentrations, and dependent upon certain other conditions, they may exhibit non-Newtonian properties. In a slurry of given particle size, the flow regimes in a pipe may vary from, say, heterogeneous suspension to homogeneous suspension, dependent upon the velocity of flow. Slurries of mixed particle size may exhibit quite different characteristics. Engineers dealing with minerals and ores will be most interested in high concentrations of settling slurries, generally flowing by saltation, or as heterogeneous suspensions in turbulent rather than laminar flow. All references are to hydraulic flow in pipes and not to any other method of flow.

Table 18 lists the variables attending conditions of flow. Table 19 gives a generalized picture of slurries, classified according to kind and the flow regimes to which they may be subjected. Figures 6 and 7 are relevant to the classification of slurries and flow regimes.

* Time Magazine, Feb. 1969.

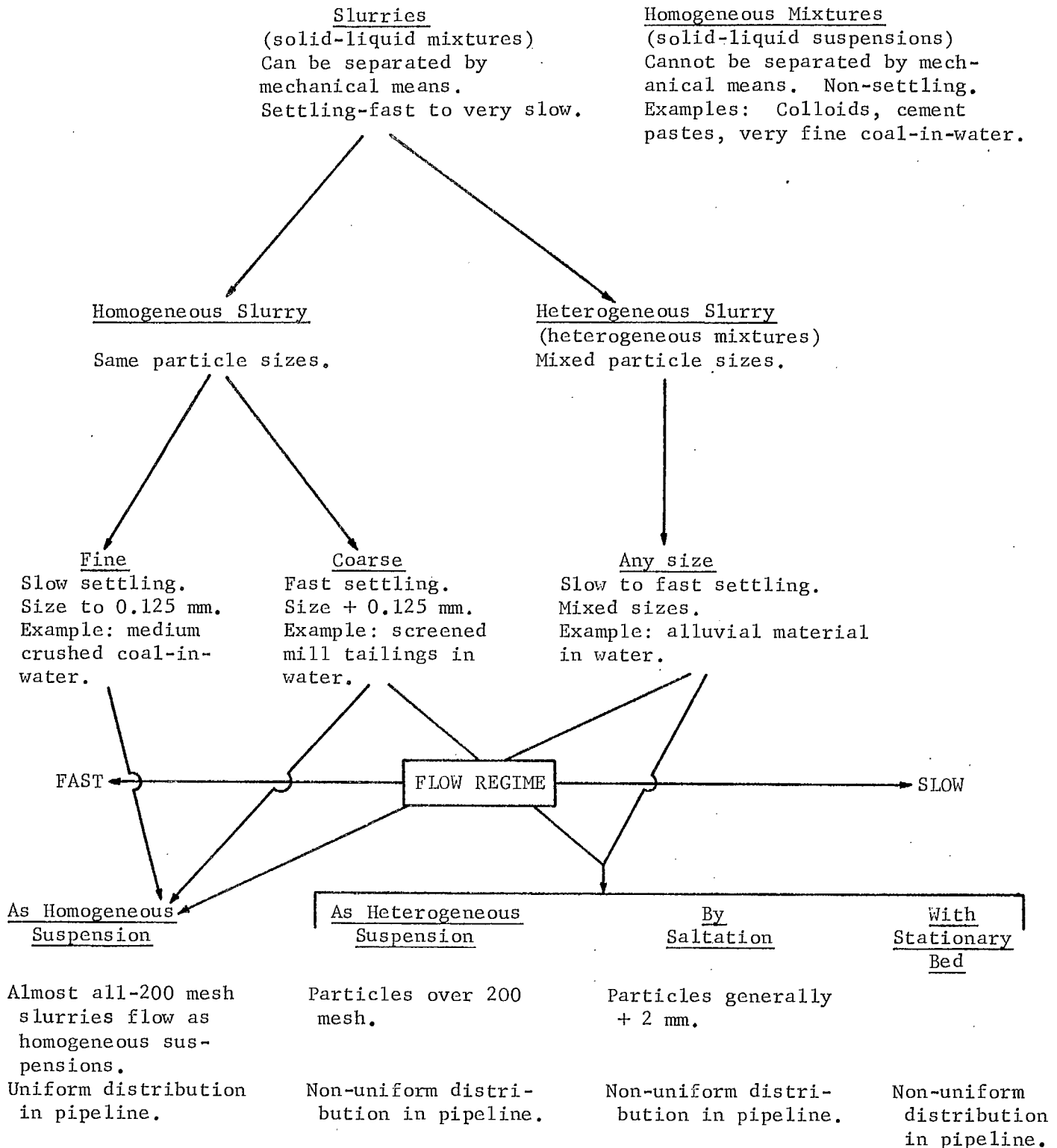
TABLE 18

Variables Affecting Condition of Pipeline Flow

Properties of solids	Properties of transporting medium	Properties of pipeline	Properties of flow
Size	Viscosity	Diameter	Velocity of transport
Shape	Density	Slope	Concentration of slurry
Size distribution	Temperature	Material	Acceleration of gravity
Density			

TABLE 19

Generalized Classification of Slurries



(For footnotes to this table, see next page.)

(Table 19, concluded) -

Footnotes to Table 19:

There seems to be no very precise terminology when dealing with solid-in-liquid mixtures or suspensions. Alternative terms are given in brackets in the table. The very fine coal-in-water non-settling homogeneous mixtures are often referred to as slurries. Non-settling conditions (for a given flow velocity) can be achieved by (1) fine grinding so that largest particle has a free falling velocity of ~ 0.005 ft/sec, or (2) obstructing the settling by increasing solids concentration, or (3) mixing particle sizes so that the smaller hinder settling of the larger.

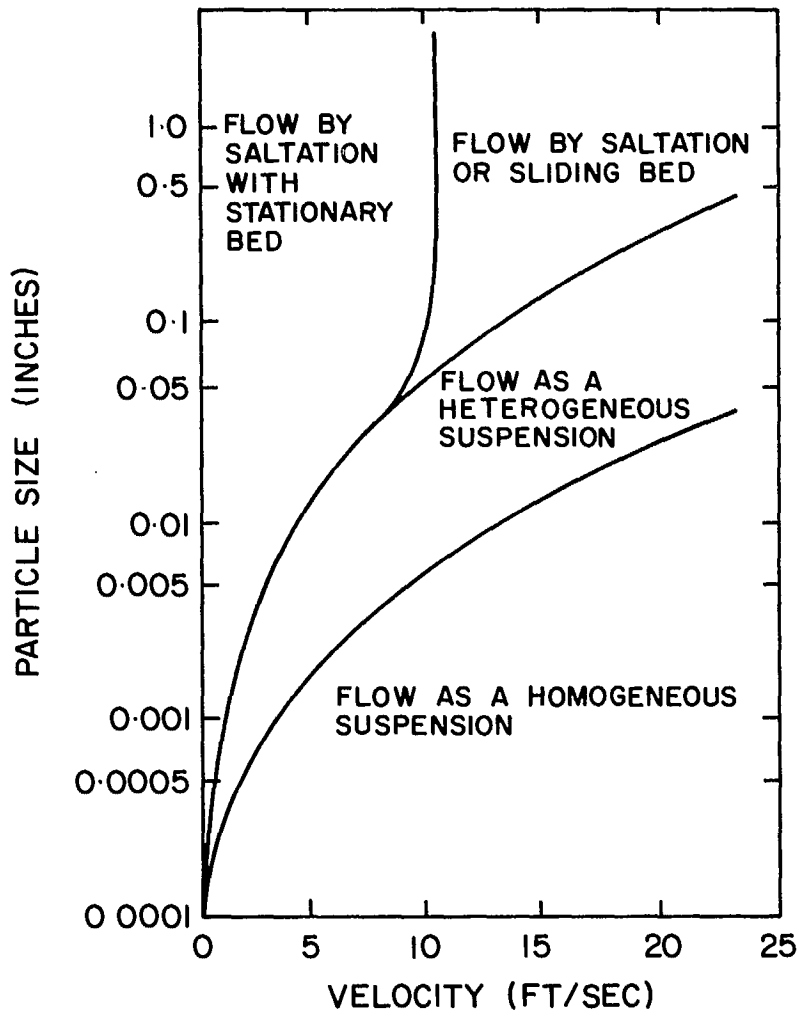


Figure 6. Four regimes of flow for sand of S.G. 2.65 in a 6-in.-diameter pipeline. (See bibl. ref. 163.)

Note: Based on experiments by Newitt in England and Govier and Charles in Canada.

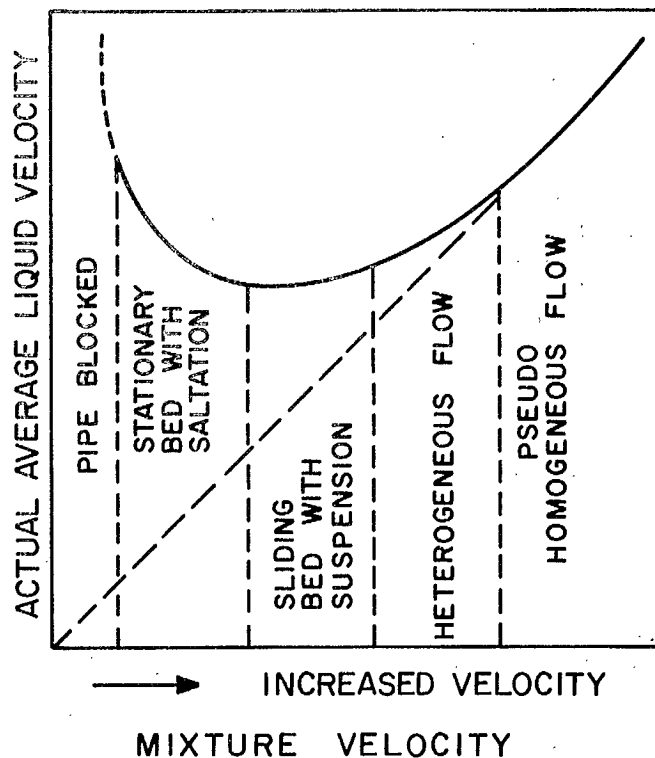


Figure 7. Schematic: flow regimes in pipelines for mixture-velocity variations. (See bibl. ref. 106.)

Note: Concentration and particle size in pipe are constant. A stationary bed with saltation causes decrease in pipe area available for liquid flow and hence increase in actual liquid velocity.

Concentration by Weight

The amount of solids present in a 2-phase (e.g. sand and water) mixture taken as a percentage of the weight of the total mixture. Concentration may also be stated in terms of volume rather than weight.

Nomograms are useful for solving concentration problems and reference should be made to Cone's article (61). The formulas used are:

$$\% \text{ concentration by weight} = \frac{100 \times \text{sg of solids}}{\frac{100}{\% \text{ conc. by volume}} + (\text{sg of solids} - 1)}$$

$$\% \text{ concentration by volume} = \frac{100}{\frac{100 \times \text{sg of solids}}{\% \text{ conc. by weight}} - (\text{sg of solids} - 1)}$$

Critical or Minimum Velocity

The average pipeline velocity below which solid particles deposit on the bottom of the pipe. The pressure gradient in a pipe is minimum at about this point. The slurry flow then becomes unstable. A line joining a number of such velocity points on a graph is known as a sediment line.

Flow by Saltation

Turbulent flow of a slurry with solids too coarse to be fully suspended. The solids move by consecutive bounces and leaps on the bottom of the pipe. Solids larger than 2 mm are usually transported by saltation, whereas those less than 2 mm are nearly always in suspension. Pebbles up to 6 in. x 9 in. are transported in the Florida phosphate fields by saltation with velocities to 18 fps.

Flow with a Stationary Bed

The flow of slurry in a pipe with a restricted area due to a deposit of solid materials on the pipe bottom.

Flow Rate

The average pipe discharge as computed from the flow velocity and the pipe diameter.

Flow Velocity

The average flow velocity as computed from the pipe discharge per unit time. The terms, actual velocity and nominal velocity, are sometimes used. Nominal velocity is that computed by using the total cross-sectional area of a pipe, whereas for actual velocity the area open to flow is used (where the pipe area open to flow has been reduced by solids settling on the bottom).

Friction Head Loss

The loss of head or pressure due to external or internal friction of the fluid flowing, and to friction caused by the solid particles being transported in suspension or by saltation. Friction head loss per unit length of pipeline is the Hydraulic or Pressure Gradient. Research on the flow of slurries at high velocities shows that the friction head loss in any pipe approaches that of water at the same high velocity (see Figures 8 and 9). Friction head loss is usually given in terms of feet of clean water but may be in feet of slurry. For a given pipe size and velocity, a change in concentration of solids by weight results in very little change in friction when given in terms of feet of slurry (provided all the solids remain in suspension), whereas the same results, in terms of feet of water, increase as the concentration of solids is increased.

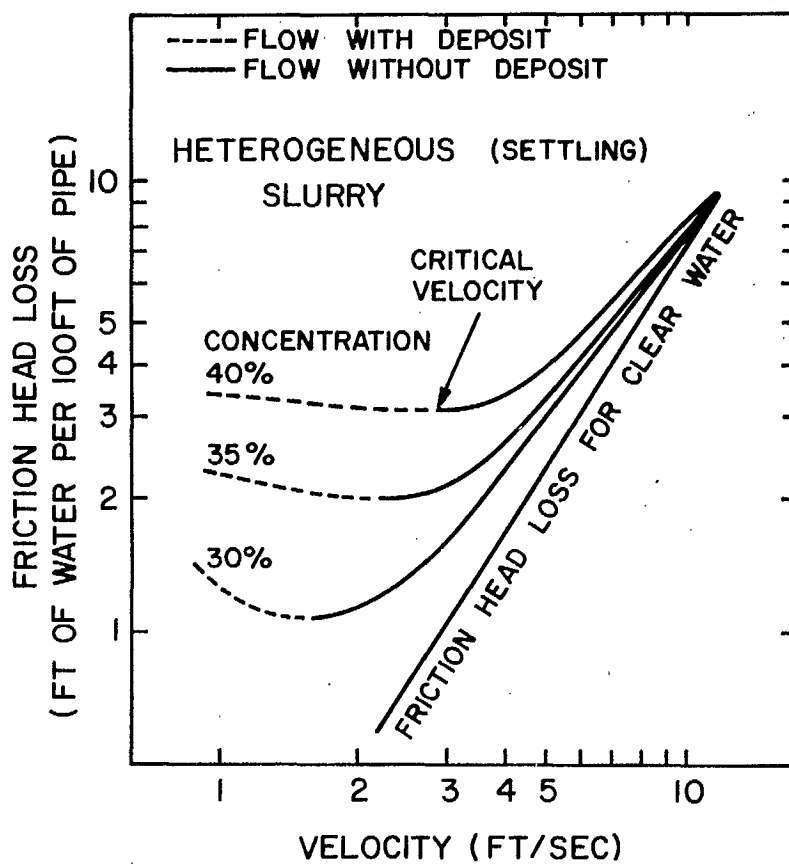


Figure 8. Friction head loss for heterogeneous slurry.
(See bibl. ref. 163.)

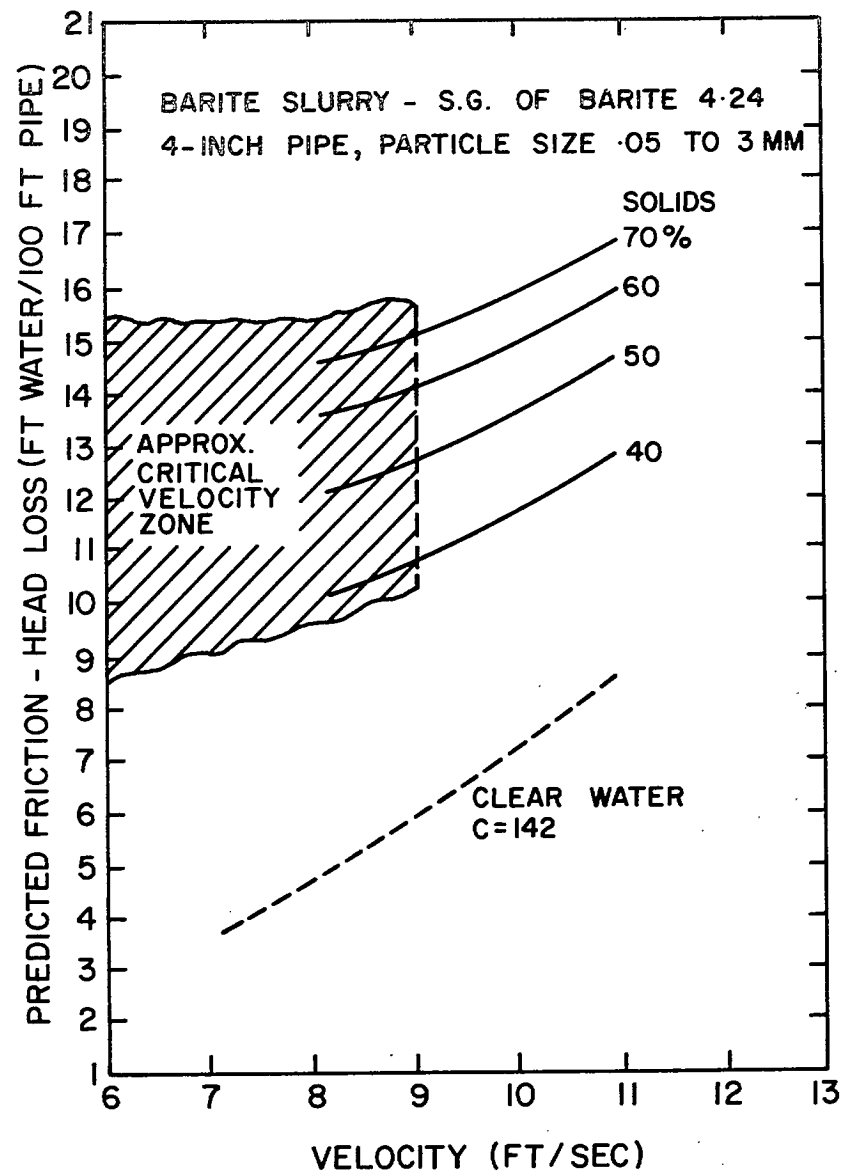
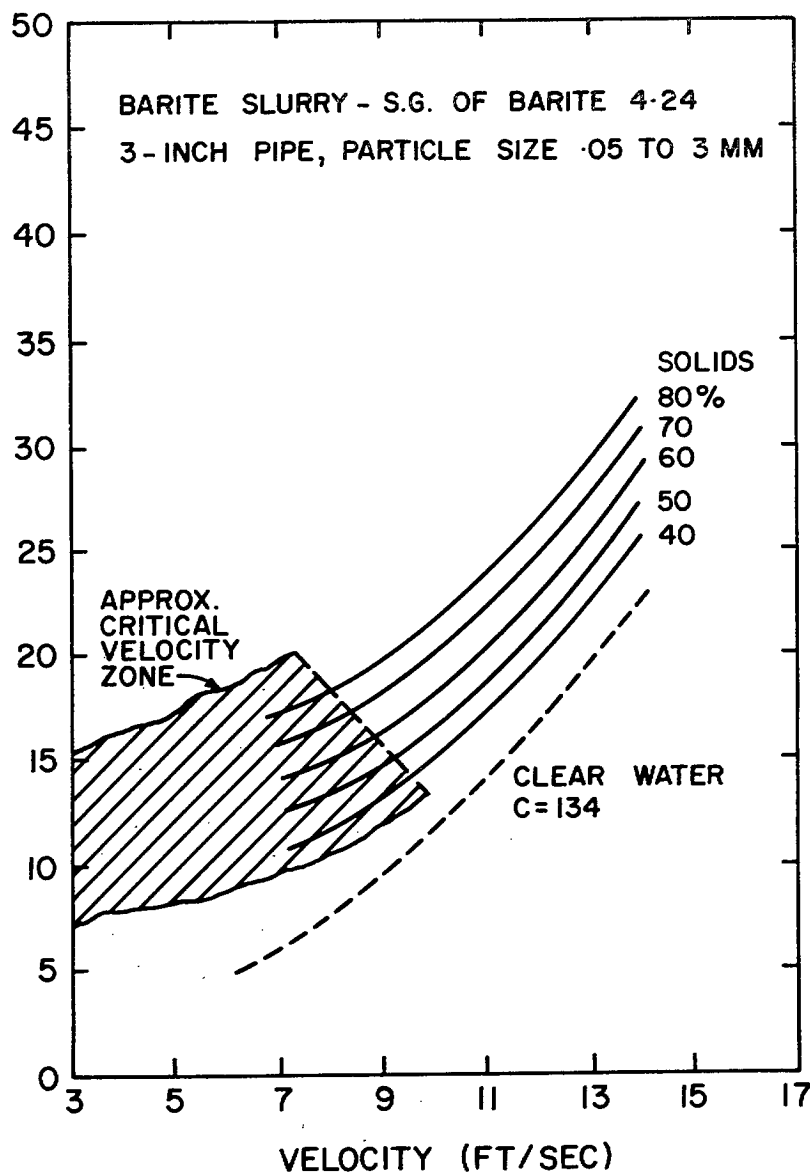


Figure 9. Friction head loss for barite slurry. (See bibl. refs. 16, 305.)

Note: Predicted friction head loss derived from quadratic formula developed by U.S. Bureau of Mines. Workers' results agree reasonably with tests in pilot plant. Test velocities ranged from 7 to 14 fps. Short test lines used.

Heterogeneous and Homogeneous Slurries

A heterogeneous slurry is here defined as one in which the solids are of mixed sizes, whereas a homogeneous slurry is one in which the solids are of the same (or nearly the same) size. With respect to flow, a heterogeneous slurry may, when there is sufficient turbulence, acquire complete and uniform suspension in the pipeline and behave as a pseudo-homogeneous slurry. Most pipelines are transporting settling slurries, such as medium crushed coal, mineral concentrates, sand, silt, and gravel. These generally settle in a stable liquid more quickly than 0.002 to 0.005 feet per second. Homogeneous mixtures such as very fine coal-in-water (also known as slurries) are non-settling; the viscous forces of the liquid can prevent or greatly attenuate the gravity settling of the solid phase. All coal slurries below 100 microns are non-settling. In such slurries, flow at low velocities is laminar, changing to turbulent at higher speeds. In general, any slurry of -200 mesh can be considered to flow as a homogeneous suspension at all velocities.

Homogeneous Mixture

A two-phase mixture of solid particles and fluid in which the two phases cannot be separated by mechanical means. Emulsions, pastes and sludges are examples. They are of interest mainly to the chemist and the process engineer. Particle size will be of 30 micron or less.

Laminar Plug Flow

Plug flow (155, 270) is of particular importance in the flow of paper pulp, solids in suspension, and oil-water and oil-gas mixtures. The Consolidation Coal Company found that the most economical and practical mode of transfer was by plug flow. Consistencies up to 60% coal by weight could be transported, provided the mixture contained 24% of fine grains (-325 mesh). In the case of laminar pipe flow of solid-liquid mixtures (Bingham Plastics), when the force applied to the pipe cross-section is lower than the yield point, the mixture is elastically compressed and water is squeezed out to the periphery of the plug much in the same manner as would occur in a compressed wet sponge. When this applied force exceeds the yield point, the plug begins to move, but remains compressed, and water serves as a lubricant between the plug and the pipe wall, with resultant reduction of friction loss. Experiments carried out by the U.S. Bureau of Mines (16, 305) have shown slurries of 40 to 80% solids to have losses in feet of mixture lower than clear water. For a given pipe velocity, friction loss is lower with plug flow than with laminar or turbulent flow.

Mesh

Mesh is the number of openings in a screen per linear inch. The U.S. and Canada have adopted as standard the Tyler 200-mesh screen where there are 40,000 openings per square inch, each opening being 0.0029 in., or 74 microns. The area of the opening of each succeeding screen in a series is $\sqrt{2}$ times that of the preceding. A micron is one millionth of a metre, or 0.00003937 in.

Newtonian Fluid

A fluid exhibiting a direct proportionality between shear stress and shear rate in laminar flow (e.g. water). Laminar flow is of little interest in connection with the flow of slurries. Most suspensions are Newtonian at low concentrations, changing to non-Newtonian when a certain critical concentration is reached. In the case of suspensions, the critical concentration depends on particle size and shape, on degree of dispersion of the particles, and on density of solids. The viscosity of Non-Newtonian Fluids (solutions, colloids) is dependent on rate of shear imposed and, in some cases, on duration of shear.

Rheology

This is the branch of science dealing with the mechanics of deformation and flow of substances, including solids and solid-liquid mixtures.

Slurry

A slurry can be defined as a two-phase mixture of solid particles and fluid in which the two phases will not chemically react with each other and in which the two phases can be readily separated by mechanical means. This definition, however, excludes such non-settling mixtures as very fine coal suspensions in water, which are commonly referred to as coal slurries. In connection with mining operations the fluid medium is always water. In general, the particle size will be in excess of 50 microns (0.002 in. approx). Most slurries encountered in practical application fall into two classes: (1) Bingham plastics which exhibit a limiting yield-stress that must be exceeded before the flow can start; and (2) pseudo-plastics, in which the movement will start no matter how small the pressure, and the viscosity subsequently changes with shear rate in a logarithmic law.

Static Head or Static Pressure

The difference in elevation between pump discharge and pipe delivery discharge.

Slimes

Slimes is a word commonly used in mining. Particle size here may be considered as -400 mesh, or 37 microns (108). Another and more precise definition is a rock product which has been ground to contain particles of not more than 5% +300 micron size nor less than 50% -75 micron size, and which includes all fine material produced by the comminution process and which has been mixed with water (242).

Transition Velocity

The velocity at which the flow of a slurry will change from one flow regime into another, such as from homogeneous to heterogeneous flow.

Turbulent Flow

Flow at high velocity, with the fluid and solid particles moving with random motion transverse to the main flow direction.

Laminar Flow

Laminar flow in a pipeline produces a streamlined effect; the velocity is distributed parabolically across the diameter of the pipe and the fluid moves in laminae or layers.

Viscosity

A measure of the resistance of a homogeneous fluid to shear between fluid particles. The apparent viscosity of a non-Newtonian fluid is the ratio between shear stress and shear rate for a particular flow rate. It is not valid for any other flow rate. For Newtonian fluids, it is the ratio between shear stress and shear rate at any flow rate.

XI. CENTRES FOR RESEARCH

The Alberta Research Council (87th Avenue and 114th Street, Edmonton 7, Alberta). The Research Council is a corporate body of the Government of the Province of Alberta, established in 1919. It operates under a 10-man council drawn from universities, government, and industry. Its annual budget is approximately \$1½ million. During 1948 the Council was engaged in the design of a semi-commercial plant to treat the Athabasca oil sands. One problem which arose was the disposal of sand tailings, and a second was the movement of heavy viscous oil in plant pipelines. It was noted that the oil would flow more readily with wet pipe walls. Investigations were carried out into the flow of sand-water suspensions in pipes and the first paper was published in 1952 (41). When in 1957 enlarged pilot plant facilities became available, further studies were undertaken into the water-wetting phenomena. Arising out of these experiments in the flow of oil and water, the subsequent capsule-in-oil projects were developed and these culminated in 1965 with the successful transport of a 514-lb metal capsule through 109 miles of 20-in. pipe carrying oil. Other studies have included the transport of coal-water slurries, coal-oil slurries, coal-paste slugs in oil, and the transport of sulphur in slugs and as a slurry. The studies were carried out in close co-operation with the University of Alberta, Edmonton. The council have published more than 300 papers and over 40 of these deal with the transport of materials by pipeline, including economic and power studies.

As a result of these successful tests, the Solid Pipeline Research Development Association (SPRDA) was formed. The SPRDA is a non-profit organization made up of thirteen firms in the fields of rail and pipeline transport, steel and pipe manufacturing, and oil, sulphur, coal and other mineral production. The formation of the Solids Pipeline Economic Study Association (SPESA) was also undertaken in connection with federal tax rulings on tax deductions for research. Federal, provincial and industry agreements were concluded and \$½ million made available to SPESA for the period of 1 year ending Mar 31, 1968. A 3,500-ft-long by 4-in.-diameter test line was erected near Edmonton with provision for carrying capsules in oil or water. The project encompasses advice on and evaluation of research data, and feasibility and economic studies, by some 9 consultant firms working under contract with SPRDA and SPESA. Over the past decade the RCA has sunk \$800,000 into pipeline transport research.

The latest information (1969) is that a new centre for the study of pipeline transport will be set up in Calgary. The new 'Institute for Pipe Line Research' would presumably incorporate the existing study groups at Edmonton and would work in conjunction with the University of Calgary.

Saskatchewan Research Council (University Campus, Saskatoon, Sask.). The Council was set up under the Research Council Act, 1954, and prescribes that at least 3 of the 21 members shall be members of the faculties of science and engineering of the University of Saskatchewan. Many of the materials produced in Saskatchewan, such as grains, potash, coal, wood pulp, and ore concentrates, have to be transported long distances to markets or seaports and are amenable to pipeline transport. Basic studies in the flow of liquid-solid mixtures were started in 1961 in co-operation with the

University of Saskatchewan. Theoretical studies are complemented by both field and full-scale tests. Potash production in Saskatchewan was expected to reach over 5 million tons by 1968 and preliminary studies of pipelining this product indicate that the method could be economical for quantities greater than 2 million tons per year. This could have considerable bearing on the ability of the Saskatchewan potash industry to sell their product in a world market where over-production and competitive pricing is the order of the day. Their Annual Reports carry a summary of work carried out each year, and a list of papers published. The work undertaken is not in any way a duplication of that carried out by the Research Council of Alberta.

The Pulp and Paper Research Institute of Canada operated a 2,000-ft pipeline loop alongside Marathon Paper Corp.'s mill at Marathon, Ontario. A study of wood-chip transport in water was carried out with a view to building a full-scale line to handle chips from forest to mill. This test was sponsored by two railroad companies, four pulp and paper companies, and two pipeline companies. No full-scale pipelines have been built to date.

Colorado School of Mines Research Foundation, Inc. (Box 12, Golden, Colo. 80402). Research is carried on in engineering and science, including studies in the transport of solids by pipelines and studies of design problems. The Colorado School of Mines Research Foundation, Inc., has published the only known textbook devoted entirely to this subject (349). It has a continuing program of studies on pipeline transport. The Stanford Research Institute (333 Ravenswood Ave., Menlo Park, Calif. 94025) is associated with Stanford University and some studies have been undertaken. The Towne School of Civil and Mechanical Engineering, University of Pennsylvania, Philadelphia, Pa. 19104, are also active in the field of research into pipeline transport.

Hydraulic transport of coal, both horizontally and vertically, has been in use for some years and a great deal of experimental work has been carried out in the U.S.A., France, the U.K., the U.S.S.R., Poland, Holland, Japan, and other countries. In the U.K. all coal mines are nationalized under control of the National Coal Board (N.C.B.). The N.C.B. Science Department (London) and the Central Electricity Generating Board carry out investigations on a large scale. The latter has, since 1959, been carrying out research into the hydraulic transport of coal from mines to power stations and has a 5-in. test pipeline in operation. Vertical transport and the design of feeders has been investigated at Woodend Colliery in Scotland (1955 and 1956).

The United States Bureau of Mines carried out extensive investigations into factors influencing the design of hydraulic backfill systems and investigated friction-head losses for sand slurries, barite and limestone during pipeline transport (16, 305). Figure 9 shows friction losses for barite. Most of their work in connection with hydraulic transport has been with coal (80, 85, 142, 172, 227, 316). A 6-in.-diameter test-line $\frac{1}{2}$ mile long is in use at the Pittsburgh Coal and Explosives Research Centers (4800 Forbes Ave., Pittsburgh, Pa., 15213). Hydraulic mining of coal is also investigated.

Another well known centre is in France. This is the Study and Research Centre of the National Coal Board (Centre d'Etudes et Recherches des Charbonnages de France - CHERCHAR, 34 rue Saint-Dominique, Paris 7^e). This is the principal research organization of the coal industry. Work is carried out at the Verneuil-en-Halatte Laboratory. The centre has a documentation service. In Belgium the comparable organization is the National Institute of the Coal Industry (Institut National de l'Industrie Charbonniere - INICHAR, 7 Boulevard Frère-Orban, Liège). This institute has a documentation service. The Dutch State Coal Mines also carry out experimental work. In Poland, research into hydraulic coal transport is centred at the Central Institute for Mining (Główny Instytut Górnictwa, Pl. Gwarkow 1, Katowice).

In Japan, studies on the hydraulic transport of coal are carried out at the Resources Research Institute (279) (Agency of Industrial Science and Technology), Kawaguchi, Saitama. The Institute of Mining Imeni A.A. Skochinskiy (Institut gornogo dela imeni A.A. Skockinskogo - IGDAN), at Moscow, is one of Russia's foremost mining institutes, where a wide range of research is carried on.

One of the foremost hydraulic laboratories is that of the British Hydromechanics Research Association (BHRI - Cranfield, Bedfordshire) (31, 32, 322, 336), where many important investigations dealing with solid-liquid pipeline flow have been undertaken. The laboratory deals in general with the industrial application of fluid mechanics; also with rock-fill dams and spillways.

An industrial establishment is the Grenoble Society for the Study and Application of Hydraulics (Société Grenobloise d'Etudes et d'Applications Hydrauliques - SOGREAH) (51, 74) 84-86 avenue Leon-Blum, Grenoble, Isère, France). This society is associated with the Etablissements Neyrpic S.A., also of Grenoble (89,91). The laboratory is known as Laboratoire Dauphinois d'Hydrauliques, Grenoble. Neyrpic Canada Ltd. and the LaSalle Hydraulic Laboratory Ltd. (0250 St. Patrick St., LaSalle) are both situated in LaSalle, Quebec. LaSalle have a branch in North Vancouver, B.C., where investigations on hydraulic transport are being carried out for commercial firms.

Universities. Experimental work is carried out from time to time in various universities, often in connection with the writing of theses. In Canada, the University of Toronto, Ontario (151, 178, 321) and Queen's University, Kingston, Ontario (38,166) have both carried out work in connection with the movement of solid suspensions in fluids. As previously mentioned, the University of Alberta, Edmonton (229) works closely with the Research Council of Alberta and the Research Council of Saskatchewan works with the University of Saskatchewan. An active centre is the Towne School of Civil and Mechanical Engineering of the University of Pennsylvania. The Imperial College of Science and the Royal School of Mines (57, 210, 211) have also carried out studies. In Australia, the University of New South Wales and the South Australian Department of Mines have developed the 'Hydro-lift' for vertical hoisting.

XII. SYMPOSIA AND CONFERENCES

The following are symposia and conferences concerned with the transport of slurries in pipelines:

1. "Colloquium on the Hydraulic Transport of Coal"; held by the National Coal Board in London, England, November 5-6, 1952. Published as proceedings, 1953.
2. "International Symposium on Solid-Liquid Flow in Pipes and its Application to Solid Waste Removal and Collection", sponsored by University of Pennsylvania and Amer. Soc. Civil Engineers, Philadelphia, Pa., March 4-6, 1968. Proceedings published as "Advances in Solid-Liquid Flow in Pipelines and its Application". (335)
3. Canadian Transportation Research Forum, Annual Meetings (Canada); that of 1968 was the fourth Canadian meeting.

Transportation Research Forum, Annual Meetings (U.S.A.); that of 1968 was the ninth for the U.S.A.
4. Symposium on The Transportation of Solids, sponsored by the South African Inst. of Mechanical Engineers, Johannesburg, November 19-21, 1969. Box 5907, Johannesburg, S.Afr.
5. Symposium on Pipeline Transportation of Slurries, at Annual Meeting, Soc. Mng. Eng., Washington, D.C., February 16-20, 1969.
6. Symposium on Pipeline Transport of Solids, sponsored by the Canadian Society for Chemical Engineering, Toronto, November 10, 1969.
7. International Conference on Transportation of Solids in Pipes (proposed). To be sponsored by BHRA (England), September 1970.
8. Data Bank: G. Govatos, of Towne School of Civil and Mechanical Engineering, University of Pennsylvania, Philadelphia, Pa., is assembling data on slurry flow in pipes. The data are stored in a computer and are available to interested persons.

XIII. ABBREVIATIONS USED IN SELECTED BIBLIOGRAPHY

abstr.	Abstract
A.E.C.	Atomic Energy Commission (U.S.A.)
Am. Ch. Soc.	American Chemical Society
Am. Inst. Mng. Eng.	American Institute of Mining, Metallurgical & Petroleum Engineers (prior to 1956, title was Am. Inst. of Mng. and Met. Eng.)
Am. Soc. Civ. Eng.	American Society of Civil Engineers
Aus. Inst. Mng. Met.	Australasian Institute of Mining and Metallurgy
Can. Ch. Process.	Canadian Chemical Processing
Can. Jr. Ch. Eng.	Canadian Journal of Chemical Engineering (formerly Can. Jr. of Technology) (The Ch. Inst. of Can.)
Can. Mng. Met. Bull.	Canadian Mining and Metallurgical Bulletin (Can. Inst. of Mng. and Met.)
Can. Inst. Mng. Met.	Canadian Institute of Mining and Metallurgy
Can. Pit & Q.	Canadian Pit and Quarry
Ch. Eng.	Chemical Engineering (USA)
Ch. Engineer	The Chemical Engineer (UK) (Inst. Ch. Eng.)
Ch. Eng. Prog.	Chemical Engineering Progress (Am. Inst. of Ch. Eng.)
Ch. Process. Eng.	Chemical and Process Engineering (UK)
Civ. Eng.	Civil Engineering (Am. Soc. Civ. Eng.)
Coal	Coal - Today and Tomorrow (USA) (also entitled Coal - Wherever Coal is Concerned)
Colliery G.	Colliery Guardian (UK)
Coal Base Metals	Coal, Gold & Base Metals of Southern Africa (South Africa)
Coal Eng.	Colliery Engineering (UK) (incorporated in Mining and Minerals Engineering from Mar. 1968)
Coal Prep.	Coal Preparation (UK)
Eng.	Engineering (UK)

Eng. Jr.	Engineering Journal (Eng. Inst. of Can.)
Eng. Mng. Jr.	Engineering & Mining Journal (USA)
H.P.A.C.	Heating, Piping and Air Conditioning (USA)
Ind. Can.	Industrial Canada
Ind. Eng. Ch.	Industrial and Engineering Chemistry (Am. Ch. Soc.)
Inst. Ch. Eng.	Institution of Chemical Engineers (UK)
Inst. Mech. Eng.	Institution of Mechanical Engineers (UK)
Inst. Mng. Eng.	Institution of Mining Engineers (UK)
Int. Symp. on Solid-Liquid Flow	See bibliographic No. 335, "Advances in solid-liquid flow in pipelines and its application"
Iron Steel Eng.	Iron and Steel Engineer (USA) (Assoc. of Iron and Steel Engineers)
Jr. Can. Pet. Tech.	Journal of Canadian Petroleum Technology (Pet. Soc. of the Can. Inst. of Mng. and Met.)
Mng. Eng.	Mining Engineering (Soc. of Mng. Eng. of the Am. Inst. of Mng. Eng.)
Mng. Congr. Jr.	Mining Congress Journal (USA)
Mng. Ch. Eng. Rv.	Mining & Chemical Engineering Review (Australia) (prior to June 1960, title was Ch. Eng. and Mng. Rv. - recently changed to Australian Mining)
Mng. Jr.	Mining Journal (UK)
Mng. Mnl. Eng.	Mining & Minerals Engineering (UK) (prior to Sept. 1964, title was Mine and Quarry Engineering)
Metal Mng. Process.	Metal Mining & Processing (USA) (prior to 1964, title was Mining World)
Mng. Tech.	Mining Technology (Am. Inst. Mng. Eng.) (Incorp. in Mng. Eng. from Jan. '49)
Mech. Eng.	Mechanical Engineering (Am. Soc. of Mech. Eng.)
Mat. Hand. Eng.	Materials Handling Engineering (USA)
N.C.B.	National Coal Board (UK)
N.R.C.	National Research Council of Canada, Ottawa

Oilweek	Oilweek (Canada)
Oil Gas Jr.	Oil and Gas Journal (USA)
Power	Power (USA)
Pr.	Proceedings
Pipe Line Ind.	Pipe Line Industry (USA)
Rock Prod.	Rock Products (USA)
Ref.	References. In Bibliography, "Ref 26" (e.g.) indicates that article lists 26 references.
R.C.A.	Research Council of Alberta, Canada (refers to paper numbers)
R.C.S.	Research Council of Saskatchewan, Canada (refers to paper numbers)
S.A. Mng. Eng. Jr.	South African Mining and Engineering Journal
S.A. Mech. Eng.	South African Mechanical Engineer
Soc. Pet. Eng. Jr.	Society of Petroleum Engineers Journal (Soc. of Pet. Eng. of the Am. Inst. of Mng. Eng.)
Tr.	Transactions
USBM IC or RI	United States Bureau of Mines, Information Circular or Report of Investigations
U.N. Conf.	United Nations Conference on the Application of Science and Technology for the Benefit of the Less Developed Areas, Geneva, 1963
World Mng.	World Mining (USA)

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(Note: Titles enclosed in parentheses are translations from the language in which originally published.)

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