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Transporting Coal in Containers Through Pipeline – A Feasibility Study

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TRANSPORTING COAL IN CONTAINERS THROUGH PIPELINE - A FEASIBILITY STUDY

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Abstract

A preliminary assessment of the feasibility of transporting coal in containers suspended in water moving through pipes - the concept of hydraulic capsule (container) pipelining (HCP) - is presented. The assessment includes technical (engineering), environmental, social and economic considerations. A tentative conclusion reached is that HCP transportation of coal is technically feasible (although it needs further research and development works), socially and environmentally beneficial, and economically justifiable in a number of situations.

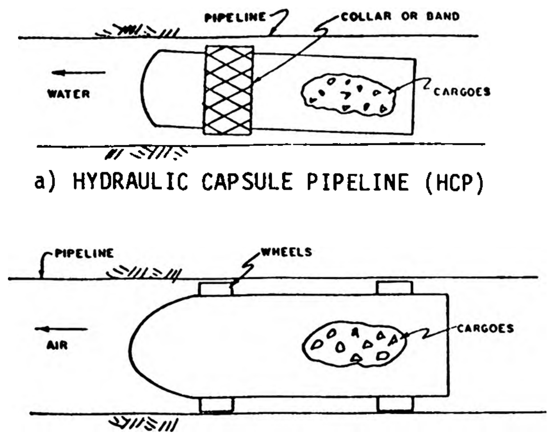
1. INTRODUCTION

According to a study completed recently by Banks for the U.S. Department of Energy (1), due to the gradual depletion of oil and natural gas in the U.S., the health of the pipeline industry of the nation after the year 2000 is not without question, if new use of pipelines is not found. The study concludes that "... to achieve significant growth, the industry must develop the capability, called freight pipeline, to move other commodities than oil and gas, i.e., bulk and packaged goods." Another conclusion reached in the report is "(freight pipeline can) induce modal shifts resulting in a reduction of total transportation energy consumption, and would offer other benefits including compatibility with high-speed rail passenger service."

The basic concept of freight pipeline has been presented by Liu and Gibson at the 4th UMR/DNR Conference on Energy a year ago (2). Putting cargoes into containers which in turn are conveyed through pipelines constitutes the basic concept of freight pipeline. The cargo-carrying containers is usually referred to as "capsules". Depending on the fluid used in the pipeline to move capsules, freight pipelines are classified as either hydraulic capsule pipeline (HCP) or pneumatic capsule pipeline (PCP).

In the case of PCP, to carry heavy cargoes, the capsules moving through pipelines must be suspended on wheels. On the other hand, for HCP no wheels are needed because the buoyancy force plus the hydrodynamic lift generated by water on capsules is sufficient for suspending capsules, even when the capsule density is greater than that of water. The manner hydrodynamic lift is generated by water on capsules was first clarified by Liu in 1977 (3). Fig. 1 (a) and (b) give the configurations of hydraulic and pneumatic capsules, respectively. The hydraulic capsules have a band (collar) near their front to increase hydrodynamic lift and to reduce frictional loss.

Both HCP and PCP have different advantages and disadvantages. Consequently, each is needed under a different set of conditions. Because PCP uses air as the working fluid, in general capsules in PCP move faster than in HCP. The optimum speed of PCP is in the range of 15-35 feet per second (4), where-



a) HYDRAULIC CAPSULE PIPELINE (HCP)

b) PNEUMATIC CAPSULE PIPELINE (PCP)

FIG. 1 TYPES OF FREIGHT PIPELINE

as for HCP capsules are usually limited to a velocity within 10 feet per second (5,6). Other advantages of PCP over HCP includes more convenience in working with air than with water, no risk in wetting the cargo or causing water to leak out of the pipe, less corrosion problems, etc. Though without using water PCP is free from these problems, the necessity for having wheels on capsules creates a new host of problems. The most serious problem is system reliability. If only a single wheel fails inside a long pipeline, the stalled capsule will tie up the entire traffic of capsules, causing a complete halt of the system. Considering the length of the pipeline and the fact that the pipeline is buried underground, it will be very difficult to remove the damaged capsule from the pipeline for repair and restart of the system. For this reason, and for the reason that PCP uses more energy than HCP (1), the application of PCP is necessarily limited to short distances.

From the foregoing comparison, it can be concluded that while PCP is more suited than HCP for short-distance transportation, the opposite holds when the pipeline is long. This shows that both HCP and PCP have a role to play in transportation, depending mainly on the transportation distance involved.

2. FEASIBILITY OF COAL TRANSPORTATION BY HCP

2.1 WHY COAL?

Transportation of coal by HCP is by no means the most promising application of HCP. In fact, due to the availability of slurry pipeline for transporting coal, many pipeline experts may wonder why one should consider coal as a potential candidate for the first application of HCP. Why not first investigate and develop HCP for transporting commodities that have higher economic value than coal but cannot be transported in slurry form? The answer to the above question is that HCP is a completely new technology not yet fully developed. All new technologies must start from a simple form, and then gradually increase sophistication as more and more about the technology are learned.

Coal transportation seems to offer an opportunity to develop the simplest type of HCP conceivable. The system is simple for these reasons: (1) Only a single cargo is involved. This makes capsule preparation and handling an easy task. (2) Accidental leakage of water into capsules has no serious consequence. (3) The bulk density of coal is such that when capsules are filled with coal, the capsule density becomes only slightly greater than water density. This minimizes contact between capsules and pipe, and optimizes energy consumption. It also makes start-up an easy task. (4) Unlike the transport of perishable commodities which require speedy delivery, speed is not needed at all for transporting coal. The only thing that counts in this case is the throughput. Even at very low speed HCP can produce an amazingly large throughput of coal (see Table 1). This offers an opportunity to run the flow

TABLE 1 - Variation of Coal Throughput of HCP with Pipeline Diameter

(Assumptions: Capsule velocity = 6 ft/sec, diameter ratio = 0.9, linefill rate = 0.9, bulk specific gravity of coal = 0.85, etc.)

Pipeline Diameter (inch)	Coal Throughput (million tons per year)
6	0.8
12	3
24	12
36	25

at rather low speed to conserve energy. At low speed the injection and handling of capsules also become easier. (5) The piping consists only of two parallel pipes connecting between a coal mine and a large power plant. No branching or telescoping of pipes are involved.

Besides being simple as discussed above, an HCP system for coal transportation also offers an opportunity for enhancing the nation's capability in transporting coal to meet increasing energy needs, and to save lives, reduce pollution, and protect environment, as will be elaborated on later.

2.2 FEASIBILITY OF HCP FOR TRANSPORTING COAL

The feasibility of engineering projects depends on (1) engineering or technical feasibility, (2) environmental and social feasibility, and (3) economic feasibility. All three must be met before an engineering project can be considered feasible and desirable. Therefore, the feasibility and desirability of HCP for coal transport will now be examined in light of these three criteria.

2.2.1 Engineering or Technical Feasibility

R & D works in HCP have been conducted in Canada by the Research Council of Alberta for more than ten years. The research activities have been centered on the hydrodynamics of HCP. As a result, today much is known about the hydrodynamics of HCP. For instance, now we know that contact friction between capsules and pipeline can be greatly reduced by using capsules with an appropriate collar as shown in Fig. 1a., by a proper matching of pipeline and capsule materials, and by running capsules at optimum speeds which depend on the density of capsules. Contrary to what one may expect, streamlining capsules has only minor effect on the drag or resistance of capsules. The energy loss in HCP is an area of hydrodynamics of HCP most thoroughly explored in Canada. Important information on the hydrodynamics of HCP may be found in (3, 6, 7, 8, 9).

The Canadian study has also encompassed the hardware components of HCP, such as the capsule pumps and the injection systems. Although the study of hardware components to date has been insufficient and inadequate, there is no conceptual problem or insurmountable difficulty remaining. As assessed by Zandi (10), "... no conceptual difficulty in freight pipeline is foreseen— if there is a problem, it is one of development."

Based on the above, and on a technology assessment conducted by the writer (2), it is concluded that using HCP to transport coal is technically feasible. In spite of this, the writer believes that an intensive R & D program lasting approximately five years is needed before the first commercial HCP system should be built. Without such an R & D program, any HCP system built will have many flaws and will be doomed to fail. The R & D in HCP should be centered on improving systems for pumping and injection, such as those proposed by the writer and his colleagues at the University of Missouri-Columbia (2,11).

2.2.2 Environmental/Social Feasibilities

The environmental and social values of HCP are most easy to demonstrate. The greatest social value of HCP is life-saving. According to the statistics compiled by the U.S. Department of Transportation (12), due to truck accidents, in 1975 there were 2,232 fatalities, 26,375 injuries, and $158,200,000 property damages. If in the future HCP can replace only 10% of the freight carried by trucks, it would mean the saving of more than two hundred lives and twenty hundred injuries per year. This will be a great contribution to society.

Other social benefits of HCP caused by reduced truck usage include alleviation of highway congestion, reducing air and noise pollutions on highways, energy conservation (2), shifting transportation energy source from oil to non-oil (the power source of HCP is electricity which need not and should not be generated from oil), etc. Concerns have been raised that with the introduction of HCP, truckers may lose their jobs in the future. The fear is unwarranted not only because HCP can replace only a small portion of truck business but also because the replacement can take place only gradually. It will take decades before enough HCPs can be built to cut into truck market substantially. What this means is that with the development of HCP, in the future fewer people will enter into truck-driving jobs; the jobs of existing truck drivers will not be eliminated. Besides, new jobs will be generated by HCP which may be more comfortable and secure than trucking jobs.

In cases where HCP will cut into railroad business, much the same as for trucks can be said, such as reduction of accidents and air and noise pollutions, saving of oils, etc. Besides, reduced usage of train for transporting coal will result in improved rail passenger services, and reduced interruption with highway and pedestrian traffic at railroad crossings. For economic reasons, unit trains that haul coal are often more than a mile long. This causes disruption of other traffic at rail crossings, especially in cities and towns.

Finally, a comparison of HCP with coal slurry pipeline is in order. Coal slurry pipeline has all the environmental and social values of HCP except the following two:

1. Slurry pipeline requires water near the source where the coal is mined. This may cause serious

problems if a regional water shortage already exists. As mentioned in a U.S. Congressional report (13), "Slurry pipelines consume large quantities of water, and, owing to the geographic location of coal, most of the pipelines originate in somewhat arid regions." For instance, great controversy surrounds the proposed 38-inch coal slurry pipeline from Wyoming to Arkansas. The main concern by the people in Wyoming and South Dakota is how this pipeline will affect the existing water users (such as the farmers) and the ground water table of the Madison Formation. This concern has been analyzed in great detail in (13), in association with congressional considerations of granting the right of eminent domain to coal slurry pipelines. On the other hand, the water in HCP is recirculated through the return pipeline which transports emptied capsules to coal mines. Once an HCP system is filled with water, it needs little replenishment.

2. Coal slurry must be dewatered at the exit terminal of the pipeline. The water released from the slurry may contain high concentration of pollutants (13). If discharged into the environment without treatment, it could cause serious pollution problems to surface and ground waters. Because the water in an HCP system is recirculated and not in contact with coal, there is no water pollution problem with HCP.

The above shows the positive impacts of HCP. The only significant negative impact happens during construction, when both the environment and the people's lives will be disrupted temporarily. However, this disruption is no more serious than the disruption caused by the construction of slurry pipeline or highway. It is a price that must be paid for increased utilization of coal.

From the above comparisons with trucks, railroad and slurry pipeline (i.e., the three principal existing modes to transport coal in large quantity over long distances), it may be concluded that HCP represents the most environmentally and socially desirable way to transport coal. Whether it is economically viable or not is a question to be discussed next.

2.2.3 Economic Feasibility

Great difficulties exist in assessing the economic feasibility of HCP. The difficulties are due mainly to the fact that HCP is still a not-yet-fully-developed technology. Notwithstanding two decades of research in HCP conducted mainly in Canada, more R & D works are required before commercial utilization is possible. The economic assessment of any undeveloped and unproven new technology is bound to be conditional and uncertain; it should not be taken without reservation. Nontheless, it is important to give some considerations to the economics of any new technology before it is developed. Such considerations are of value not only to the policy maker who must decide whether to support the development of a new technology, but also to the researchers themselves who must make a choice among several alternatives about the best way to accomplish the same goal.

As is well-known by transportation experts, the cost of any ground transportation system depends on many important variables such as river crossings (the number of crossings and the size of the rivers), topography (whether the route crosses mountain or whether the land is hilly or not), land value (urban or rural setting), climate (cold or warm, wet or dry), availability of construction materials, etc. Different transportation modes depend on each of these factors in a different manner. For instance, because railroads cannot have large slopes, they are very expensive to build in hilly areas. The same does not hold for pipelines which can have much greater slopes without any adverse effect. Therefore, it is impossible to compare the costs of two transportation modes in general. One mode may be more economical under one set of conditions, whereas the opposite may be true under a different set of conditions. This is clearly illustrated in the economic comparison of slurry pipeline with rail as given in the congressional report on slurry pipeline mentioned before (13). Of the four cases studied in the said report, two cases (the Wyoming-to-Texas, and the Tennessee-to-Florida lines) turned out in favor of slurry pipeline, whereas the other two cases (the Montana-to-Minnesota, and the Utah-to-California lines) turned out in favor of railroad. Note that in all the four cases, the cost of building railroads was not considered. It was assumed that existing railroads can be used. To build new railroads merely for transporting coal would be clearly uneconomical in most situations.

In spite of the aforementioned great difficulties in comparing different modes, a comparison may sometimes offer an insight, as will be shown next.

Generally, pipelines provide one of the most economic ways to transport materials. For example, according to Hirst (14), the price for inter-city freight transport by ordinary (liquid) pipelines in 1970 was 0.27¢ per ton-mile. The corresponding figures for railroad and truck were respectively 1.4 and 7.5¢. This means transportation of freight by rail and trucks are respectively 5 and 28 times more expensive than by ordinary pipelines. Although the transport of solids by HCP is bound to be more expensive than the transport of liquid by pipelines, it is likely that under favorable conditions HCP transportation cost will be less than 28 times or even 5 times the transport cost of ordinary pipeline. This means it is likely that under favorable conditions coal transportation by HCP may turn out cheaper than by truck and railroad.

In the ensuing discussion, an economic comparison will be made between coal slurry pipeline and HCP. In general, slurry pipelines require large investment on the facility for slurry preparation at the pipeline intake, and even a larger investment on the dewatering facility at pipeline exit. In addition, large costs are encountered for the power required for slurry preparation and dewatering, and for the purchase of flocculants used in the dewatering process. All these expenses are independent of the length of the pipeline. On the other hand, two major items of HCP which cost more than slurry pipeline are pipeline cost (due to the need for a return pipeline) and container cost - an item which does not exist for slurry pipeline. The costs for these two items are directly proportional to pipeline length. Because what makes slurry pipeline more costly is independent of pipeline length whereas what makes HCP more costly depends on length, it is expected that slurry pipeline will be more economical than HCP when transportion distance is long, whereas the opposite may hold for short-distance transportation. Of course, the distance of HCP cannot be too short or it may lose competitiveness to trains or trucks.

For a further analysis, consider the four HCP systems listed in Table 1, and compare them with four coal slurry pipelines of equivalent throughputs.

First, consider the costs of the terminus facilities (i.e., the facilities at both ends of the pipeline). For the slurry systems, this includes dewatering facility and slurry preparation facility. Their approximate costs can be determined from throughputs by using Fig. 10 of Reference 13. These costs are listed in Table 2, together with their totals. The terminus-facility costs for the corresponding HCP systems are also listed. It appears that the terminus-facility cost for HCP is often less than one-tenth of that for slurry pipeline. The HCP costs listed were obtained from a direct estimate of each part and component of the system illustrated in Fig. 2, including the costs for equipment (hoppers, trolleys, conveyor belts, etc.), purchase of land, terminus buildings, construction costs, and 18% provision for engineering, inspection, and contingencies.

TABLE 2 - Comparison of Slurry Pipeline with HCP about Costs of Terminus Facilities (Million Dollars)

Item	Throughput (Million Tons Per Year)			
	0.8	3.0	12	25
Slurry Pipeline Termini:	6	21	66	118
Dewatering Facility	4	13	43	78
Slurry-Preparation Facility	2	8	23	40
HCP Termini	2.0	2.5	3.5	5.0

Next, compare the operational and maintenance costs of HCP with those of the slurry pipeline. It is expected that due to the need for loading and unloading of capsules, HCP is more labor-intensive than slurry pipeline. This mean labor cost for HCP must be higher than that of slurry pipeline. Because the ultimate degree of automation of HCP cannot be predicted with certainty at this stage, the labor costs of HCP estimated herein are based on three levels of automation: low (1,000 workers), medium (200 workers), and high (50 workers). The results are listed in Table 3. The corresponding labor costs for the slurry pipeline listed in Table 3 are those taken from Figs. 13 and 14, Reference 13.

Note that the labor costs are generally much higher for HCP than for slurry. Counterbalancing the higher labor costs is the lower cost for power consumption for HCP termini. The large consumption of power at slurry-pipeline termini is mainly the result of the need for pulverizing coal at the slurry intake terminus and to dewater coal at the exit terminus. Both the power cost and the cost for flocculants for slurry pipeline are those found from Figs. 13 and 14, Reference 13. Note that general adminis-

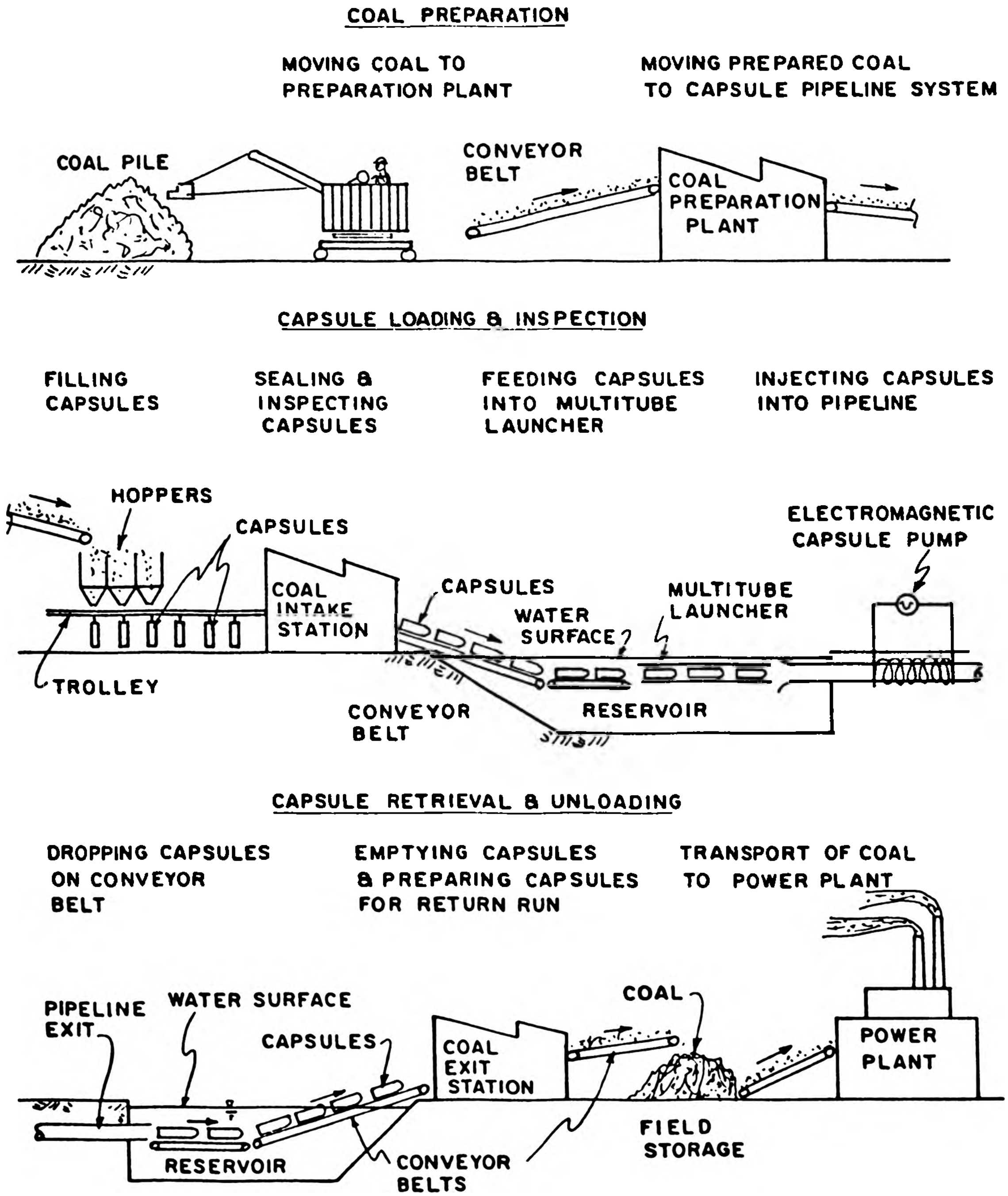


FIG. 2 CONCEPT ON HYDRAULIC-CAPSULE-PIPELINE (HCP) TRANSPORT

TABLE 3 - Comparison of Slurry Pipeline with HCP about Costs for Operation of Termini (Million Dollars per Year)

Item	Throughput (Million Tons per Year)			
	0.8	3.0	12	25
HCP Labor Cost:				
Low Automation	20	20	20	20
Medium Automation	4.0	4.0	4.0	4.0
High Automation	1.0	1.0	1.0	1.0
Slurry Pipeline Labor Costs:	1.0	1.3	2.9	4.7
Dewatering Facility	0.5	0.7	1.5	2.5
Slurry Preparation Facility	0.5	0.6	1.4	2.2
HCP Termini Energy Cost	0.2	0.4	0.6	0.8
Slurry Termini Energy Cost:	0.7	2.1	6.4	11.2
Dewatering Facility	0.4	1.1	3.5	6.0
Slurry Preparation Facility	0.3	1.0	2.9	5.2
Slurry Flocculants Cost	0.2	0.7	3.0	5.7
Total HCP Terminus Operation and Maintenance Costs:				
Low Automation	20.2	20.4	20.6	20.8
Medium Automation	4.2	4.4	4.6	4.8
High Automation	1.2	1.4	1.6	1.8
Total Slurry Pipeline Terminus Operation and Maintenance Costs	1.9	4.1	12.3	21.6

tration cost and the costs for maintenance materials and supplies are estimated to be the same for HCP as for slurry pipeline. Since they are judged to be the same, they need not be listed in Table 3 for comparison purposes.

The cost values listed in Tables 2 and 3 are those independent of pipeline length. On the other hand, cost values that depend on the length of the pipe are listed in Table 4. These include pipeline cost, capsule cost, and the cost of power for pumping. The costs of pumps and the pumping station, and the cost for maintaining pumping stations are not included because they are assumed the same for HCP as for slurry pipeline. Due to the use of dual pipelines in HCP, the pipeline cost of HCP is assumed to double that of slurry pipeline given in Fig. 11, Reference 13. This is slightly conservative because the costs for excavation, backfill, and right-of-way should be essentially the same for a dual-pipeline system as for a single pipeline. The capsule cost is estimated to be 2.5 times the pipeline steel cost. The power cost per year for pumping capsules is estimated to be three times higher than for slurry. This is based on the conservative assumption that HCP pumps are 50% less efficient than slurry pumps.

TABLE 4 - Comparison of Slurry Pipeline with HCP About Costs of Pipeline, Capsule, and Pumping Power (Million Dollars per 100 Mile)

Item	Throughput in Million Tons per Year			
	0.8	3.0	12	25
Pipeline Costs (Including Steel, Excavation, Welding, Installation, Right-of-Way, etc.):				
Slurry Pipeline	12	16	31	54
HCP	24	32	62	108
Capsule Costs	12	19	44	85
Pumping Power Cost (per year):				
Slurry	0.5	1.0	2.0	3.0
HCP	1.5	3.0	6.0	9.0

Finally, assuming the life-time of both HCP and slurry pipeline to be 30 years, the previously analyzed costs can be converted to equivalent annual costs. For transportation distance of 100 miles, the results based on annual costs are listed in Table 5. Values in Table 5 indicate that when the throughput is high and when the system has at least a medium degree of automation, HCP can be more economical than slurry pipeline for transporting coal. For instance, even at

TABLE 5 - Comparison of Slurry Pipeline with HCP on Annual Basis for 100 Miles of Pipes (million dollars per year)

Item	Throughput (Million Tons per Year)			
	0.8	3.0	12	25
Slurry System:				
Terminus Facilities	0.20	0.70	2.2	3.9
Terminus Operation and Maintenance	1.9	4.1	12.3	21.6
Pipeline	0.40	0.53	1.0	1.8
Pumping Power	0.5	1.0	2.0	3.0
HCP System:				
Terminus Facilities	0.07	0.08	0.12	0.17
Pipeline	0.80	1.07	2.07	3.60
Capsules	0.40	0.63	1.47	2.83
Pumping Power	1.50	3.0	6.0	9.0
Terminus Operation:				
Low Automation	20.2	20.4	20.6	20.8
Medium Automation	4.2	4.4	4.6	4.8
High Automation	1.2	1.4	1.6	1.8
Total for Slurry System	3.0	6.33	17.5	30.3
Total for HCP System:				
Low Automation	23.0	25.2	30.3	36.4
Medium Automation	7.0	9.2	14.3	20.4
High Automation	4.0	6.2	11.3	17.4

"medium automation" (i.e., requiring two hundred employees to run an HCP pipeline), the total cost of the system for transporting 25 million tons of coal per year will be about ten million dollars a year cheaper for HCP than for slurry pipeline.

The foregoing economic analysis may be extended to other transportation distances. Table 6 summarizes the results based on four different distances: 50, 100, 200 and 500 miles. From Table 6, at 500 miles, HCP always turned out more expensive than slurry pipeline. However, within the distance range 50-200 miles, HCP is more economical than slurry under one set of conditions, whereas the opposite holds under different conditions. Generally speaking, longer distances tend to favor slurry pipeline, and larger throughputs tend to favor HCP.

TABLE 6 - Summary of Cost Comparison Between Slurry Pipeline and HCP Transportation of Coal

Transportation System	Transportation Distance (miles)	Throughput (tons per year)			
		0.8	3.0	12	25
Slurry	50	2.6	5.6	16.0	27.9
	100	3.0	6.3	17.5	30.3
	200	3.9	7.9	20.5	35.1
	500	6.6	12.5	29.5	49.5
HCP (Low Automation)	50	21.6	22.8	25.5	28.7
	100	23.0	25.2	30.3	36.4
	200	25.7	29.9	39.8	51.8
	500	33.8	44.0	68.4	98.1
HCP (Medium Automation)	50	5.6	6.8	9.5	12.7
	100	7.0	9.2	14.3	20.4
	200	9.7	13.9	23.8	35.8
	500	17.8	28.0	52.4	82.1
HCP (High Automation)	50	2.6	3.8	6.5	9.7
	100	4.0	6.2	11.3	17.4
	200	6.7	10.9	20.8	32.8
	500	14.8	25.0	49.4	79.1

3. CONCLUSION

The following tentative conclusions have been reached:

1. Transportation of coal by HCP is technically feasible although more research and development are needed before an efficient and reliable HCP system can be built. It is estimated that a small crash program of R & D costing approximately five million dollars and lasting about five years is needed for the development of HCP for coal transportation.

2. Although coal transportation is by no means the most promising application of HCP, it is technologically simpler than other applications and hence should be made the first HCP application. After HCP has been developed and used successfully for transporting coal, adaptation of the system for transporting other special cargoes or for use as a general cargo transportation system for intercity freight transport is expected to follow.

3. Of all the important methods for distant transport of coal, HCP is clearly the most environmentally and socially desirable method. The method saves energy, does not use oil, does not cause air, water and noise pollutions, saves lives, reduces traffic and accidents on highways and railroads, and does not consume water.

4. HCP transportation of coal is economically feasible when the throughput is large (say, at least greater than 1 million tons per year) and when automation is applied to the system. The practical range of HCP for transporting coal seems to be in the range 50-300 miles. At distances greater than 300 miles, HCP is likely to lose its competitiveness to slurry pipeline if water for the slurry pipeline is readily available. On the other hand, at distances less than 50 miles, it is expected that HCP will lose competitiveness to truck, train, and PCP.

5. The economics of HCP depends greatly on the automation of the system and the efficiency of the HCP pumps. Therefore, research directed towards improving the efficiency of HCP pumps and increasing the automatic handling capacity of capsules are of upmost importance for the development of HCP.

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5. ACKNOWLEDGEMENT

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6. BIOGRAPHICAL SKETCH

Henry Liu is Professor of Civil Engineering, University of Missouri-Columbia. Born in Peking, China, in 1936, Liu earned his B.S. degree from National Taiwan University in 1959, and M.S. and Ph.D. from Colorado State University in 1963 and 1966, respectively. He first joined the University of Missouri in 1965 as Assistant Professor of Civil Engineering. In 1975, he became a U.S. citizen.

Liu's specialty is hydraulics/fluid mechanics. He has published more than twenty technical papers and directed several research projects. He is currently the Chairman of the Aerodynamics Committee of the American Society of Civil Engineers (ASCE), and a member of the Hydromechanics Committee of ASCE. He is a registered P.E., and his biography appears in numerous regional, national and international Who's Who.