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ENERGY CONSERVATION VALUE OF HYDRAULIC CONTAINER PIPELINE(HCP)

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FOREWORD

In June 1978, the University of Missouri-Columbia received a research contract (EM-78-5-02-4935) from the U.S. Department of Energy to investigate the feasibility of HCP (Hydraulic Container Pipeline)* as a viable means of freight transport that conserves energy. HCP is a particular type of freight pipeline which transports cargoes in containers moving through pipelines filled with liquid--usually water. It is a new concept of freight transport originated in Canada in the 1960's. Potential advantages of this new mode of transport includes (1) energy conservation, (2) pollution free, (3) reduction of highway and railroad accidents, (4) automation (5) no interruption by adverse weather, and (6) protection of environment.

The four tasks of the contracted research are: (1) assessment of energy conservation value of HCP as compared to other modes of freight transport such as trucks, railroad, and slurry pipeline, (2) assessment of the market of HCP for coal transportation, (3) development of design concepts on HCP for transporting coal, and (4) design and construction of a small HCP system for the demonstration of the concept of HCP transportation. This report deals with the first task only. Another report,, "Transportation of Coal by Hydraulic Container Pipeline (HCP)--A Feasibility Study," will be prepared to deal with the other tasks.

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*Hydraulic container pipeline is usually referred to as "hydraulic capsule pipeline" or simply "capsule pipeline." In this report the terms "capsule" and "container" will be used as synonyms.

ABSTRACT

The purpose of this sponsored research is to assess the feasibility and the potential value of HCP (Hydraulic Container Pipeline) as a new mode of freight transport. The tasks of the study involve (1) assessment of the energy conservation value of HCP as compared to other modes of freight transport such as truck, rail and slurry pipeline, (2) assessment of the market of HCP for coal transportation, (3) development of design concepts on HCP system for transporting coal, and (4) design and construction of a small HCP system for the demonstration of the concept of HCP transportation.

To date, the first three of the four aforementioned tasks have been completed; task 4 has just begun. This report deals with the first task only. Another report, entitled "Transportation of Coal by Hydraulic Container Pipeline (HCP)--A Feasibility Study," deals with tasks 2 and 3.

It is shown in this report that HCP possesses high potential for conserving energy used in freight transport and reducing U.S. reliance on oil.

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Energy Conservation Value of Hydraulic Container Pipeline (HCP)

I. PURPOSE OF STUDY AND METHODOLOGY

The purpose of this study is to determine the energy conservation value of HCP (Hydraulic Container Pipeline) as a new mode of freight transport. To accomplish this, the EI (Energy Intensiveness) and the ECI (Energy Cost Intensiveness)* of HCP are compared to the EI and ECI of other modes of freight transport such as slurry pipeline, truck, rail, waterway, airplane, and PCP (Pneumatic Container Pipeline). Then, the potential of HCP for conserving energy in the transportation industry is assessed. The value of HCP as a means to reduce dependence on oil is also discussed.

II. SUMMARY OF FINDINGS

From a comparison of the EI and ECI of different modes, it is concluded that under most conditions HCP uses far less energy than slurry pipeline and trucks. Large systems of HCP also use less energy than rail and waterways. Therefore, the development of HCP for commercial use can produce great saving of energy (trillions of Btu's per year) and oil (billions of gallons per year), resulting primarily from reduced usage of truck, rail, and slurry pipeline.

Although HCP also uses less energy than PCP, and much less energy than air-freight, no saving is expected here because both PCP and air-freight are needed for fast delivery of special cargoes.

While the greatest market for HCP seems to be intercity transport of freight--the same freight now being transported mainly by trucks--the most immediate

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*See Section III for the definition and significance of EI and ECI.

application of HCP seems to be transportation of coal over distances in the range between 20 and 300 miles.

III. SIGNIFICANCE OF EI AND ECI

Energy Intensiveness (EI) is the energy consumed in the transport of unit weight of cargo over unit distance. It is an index of the energy efficiency of transportation systems. A common unit of EI is Btu/TM.* Quite a bit of controversy exists in the use of EI. For instance, Zandi and Kim [1]** criticized some common usage of EI based on national averages: "(1) It represents an almost useless average value, and (2) it signifies energy consumption in only a portion of the system." Due to these controversies, an analysis of the significance and limitations of EI is provided as follows:

First, consider the fact that EI represents only a portion of the energy used. Hirst [2] gave the value of EI of different modes of freight transport as shown in Table 1. These values of EI were computed by using a

TABLE 1 - Energy Intensiveness (EI) for Various Modes of Freight Transport (Approximate Values for mid-1960's)

Mode	EI (Btu/TM)
Air Freight	37,000
Truck (Intercity)	2,300
Railroad	680
Waterway	540
Pipelines (Oil)	450

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*TM stands for ton-mile.

**Numerals in [ ] refer to corresponding items in APPENDIX 1 - REFERENCES.

somewhat arbitrary standard. For instance, the value of EI for truck given in Table 1 was obtained from the energy of the diesel fuel used for transporting one ton of cargo over one-mile distance. The energy of the fuel is that released from combustion; it does not include the energy needed for producing the fuel (drilling, pumping oil from underground, refining, etc.), and for transporting the fuel over long distances to the filling station. This arbitrariness is perfectly acceptable when comparison of EI is made between truck and train, for both use the same kind of fuel for propulsion and hence consume the same amount of energy in drilling, refining, etc. No matter whether those additional consumptions are included or not, the difference in EI between the two modes (truck and train) remains the same. Therefore, the fact that EI represents the energy consumed by only a portion of the system is harmless when EI is used to compare two modes based on the same fuel or energy source.

However, when comparing the EI of pipeline with that of truck and train, the situation is much more complex. Because pipeline uses electricity which usually is not generated from oil, the difference in EI between pipeline and truck (or train) is almost impossible to ascertain. The difference depends not only on whether one includes the extra energy used in the preparation and transportation of oil, but also on what to include for the energy consumed in the generation of electricity. Assuming the electricity to be generated from coal, one should include for instance the energy lost in generation and distribution of electricity, and the energy needed to mine, prepare, and transport coal to power plants. Even so the comparison of EI between the two modes would still be of questionable value because one Btu of energy from oil costs more than one Btu of energy from coal.

To provide a meaningful comparison of the energy conservation value of two modes of transport based on different fuels, a new quantity similar to EI, but taking into account the price of fuels, must be defined. This can be seen from the following example:

Suppose a particular HCP system has a value of EI = 1,000 Btu/TM, based on the energy of the coal used in generating electricity. How do we compare the energy conservation value of this system with an alternate railroad system having EI = 500 Btu/TM?

Assume the electricity used in the HCP system is generated from coal, whereas the EI for rail comes from diesel fuel. The price of one Btu energy coming out from coal is

$$C_1 = \frac{P_1}{E_1} \tag{1}$$

where P_1 = unit price of coal ($/ton);
E_1 = energy content of coal (Btu/ton)

Likewise, the price of one Btu energy released from diesel fuel is

$$C_2 = \frac{P_2}{E_2} \tag{2}$$

where P_2 = unit price of diesel ($/gal);
E_2 = energy content of diesel (Btu/gal).

Based on current price and average conditions, we have approximately:

$$P_1 = \$30 \text{ per ton},\ P_2 = \$0.5 \text{ per gal},\ E_1 = 2.5\times10^7 \text{ Btu/ton and}$$
$$E_2 = 1.4\times10^5 \text{ Btu/gal.}$$

Substituting the above values into Eqs. 1 and 2 yields $C_1 = \$1.2\text{x}10^{-6}/\text{Btu}$ from coal, and $C_2 = \$3.6\text{x}10^{-6}/\text{Btu}$ from diesel. This shows one Btu from diesel is about three times as expensive as one Btu from coal.

Now, define 'energy cost intensiveness', abbreviated as 'ECI', to be the fuel cost in dollars for transporting one ton of cargo over a one-mile distance. Since the EI for the HCP system is 1,000 Btu/TM, the ECI for the system is

$$(\text{ECI})_1 = C_1(\text{EI})_1 = 1.2\text{x}10^{-6}\text{x}1000 = \$1.2\text{x}10^{-3}/\text{TM} = 1.2 \text{ mills/TM}.$$

Likewise, for the alternate rail system,

$$(\text{ECI})_2 = C_2(\text{EI})_2 = 3.6\text{x}10^{-6}\text{x}500 = \$1.8\text{x}10^{-3}/\text{TM} = 1.8 \text{ mills/TM}.$$

This shows even though the EI for the HCP system is twice as high as that for rail, the ECI for HCP still turns out less than for rail. This of course is due to the fact that the price of energy from diesel is three times as high as that from coal.

The above example shows that a meaningful comparison of the energy efficiency of transportation systems based on different fuels is possible provided that ECI is used in lieu of EI. Therefore, henceforth, comparison of HCP with slurry pipeline which also uses electricity will be based on EI, whereas comparison of HCP with truck, trains, waterways, etc. which use diesel or other petroleum products will be based on ECI.

Next, consider the matter of the variation of EI and ECI within each mode. The values of EI listed in Table 1 for various modes are the average values for the nation. A large variation of EI within each mode is expected when pertinent conditions vary. For example, trucks consume much more energy when traveling on winding roads in the mountains than on superhighways on the prairie. Therefore, when for instance considering a particular road which crosses a peak of the Rocky Mountains, the value of EI for such a road is bound to be much greater than the 2,300 Btu/TM given in Table 1. This does not mean that the values given in Table 1 are meaningless; it only means that they must be taken in proper perspective and used in a correct manner. For instance, a meaningful conclusion one can reach from the values given in Table 1 is that on the average trucks use much more energy than trains. There may be exceptions to this rule in particular instances, but on the average this is expected to hold. In the case of pipelines, although EI varies greatly with pipe diameter and the speed of the flow, again the average value given in Table 1, if interpreted correctly, can be rather useful. The figures in Table 1 indicate that generally pipelines used commercially for long distance transport of oil (this is usually in the diameter range of 1 to 3 feet and speed range of 1 to 10 feet per second) have a much lower value of EI and hence use less energy than trucks to transport the oil.

The above shows that nothing is wrong in the basic concept of EI or ECI; they just need to be used carefully, and the results interpreted correctly. Indiscriminate use of EI or ECI can of course result in misleading or incorrect conclusions. This report attempts to compare the EI and ECI of different modes of freight transport with HCP only when a comparison is meaningful. The reader should read the report carefully to avoid misinterpretation of results or taking isolated statements out of context.

IV. EI AND ECI OF VARIOUS MODES OF FREIGHT TRANSPORT

A. Hydraulic Container Pipeline (HCP)

1. Frictional Loss Along HCP and Energy for Pumping

The frictional loss along HCP depends on many complicated factors such as capsule geometry, capsule-pipe diameter ratio, capsule-fluid density ratio, capsule speed, capsule material, pipe material and roughness, etc. To date, it is not yet possible to predict the frictional loss along HCP from these factors. Accurate prediction of frictional loss is possible only for specific capsules under conditions tested before. Most of these tests were conducted in Canada by Alberta Research Council; a summary of the test results is contained in [3]. The EI for HCP can be determined from test data of frictional loss in the following manner:

Refer to APPENDIX 2 for the definitions of symbols used in this report. The bulk discharge (i.e., the discharge including both capsules and the fluid) is

$$Q_b = \frac{AV_c}{v} \tag{1}$$

in which we may use cfs, ft^2 and fps respectively for the units of Q_b, A and V_c. The power required to overcome frictional loss along unit length of the pipe is

$$P = Q_b S_f = \frac{AV_c\ S_f}{v} \tag{2}$$

When S_f is in psi/ft and P in Btu/sec-mile, Eq. 2 must be rewritten as

$$P = \frac{AV_c S_f}{v} \left(\frac{144 \text{x} 5280}{778}\right) = 977\ \frac{AV_c S_f}{v} \tag{2a}$$

The number of capsules going through the pipe per second is

$$n = \alpha \frac{V_c}{L_c} \tag{3}$$

The discharge of capsules through pipe is

$$Q_c = \alpha A_c \; V_c \tag{4}$$

The throughput of cargo is

$$W = \varepsilon \; \gamma s \; Q_c = \varepsilon\alpha\gamma s \; A_c V_c \tag{5}$$

If the units of W, A_c and V_c are respectively tons/sec, ft^2 and fps, and if γ = 62.4 lbs/ft^3 (water), then Eq. 5 becomes

$$W = \left(\frac{62.4}{2{,}000}\right) \varepsilon\alpha s \; A_c V_c = 0.0312 \; \varepsilon\alpha s \; A_c V_c \tag{5a}$$

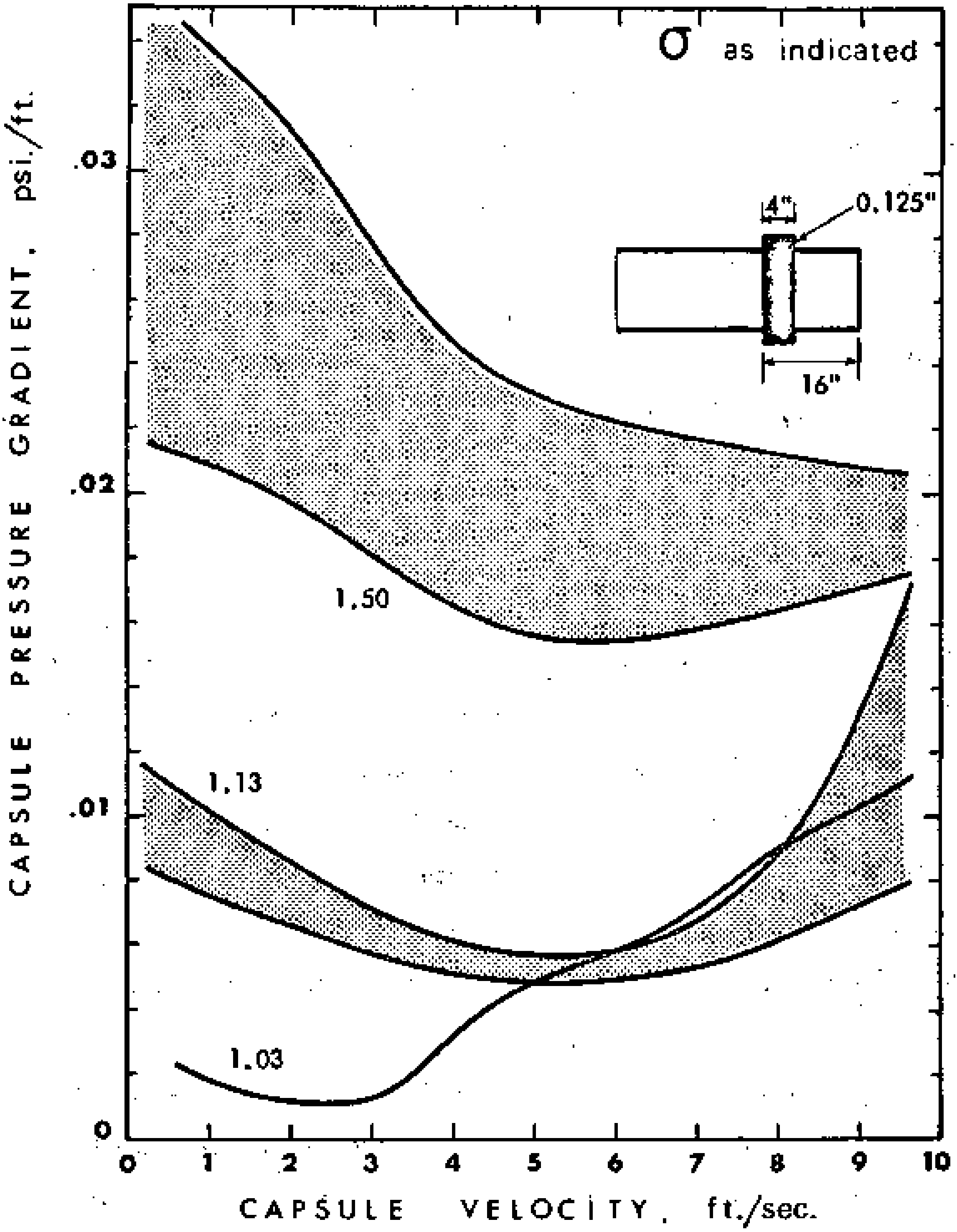
From the above, for HCP which uses water as fluid, the energy intensiveness is

$$EI = \frac{P}{W} = (3.13\text{x}10^4) \; \frac{S_f}{\varepsilon\alpha s v \; k^2} \tag{6}$$

where S_f is in psi/ft, and EI is in Btu/TM. The quantities ε, α, s, v and k are all dimensionless.

Eq. 6 may be used to compute the EI of HCP. Note that the largest HCP ever tested is a 10-inch pipeline in Canada by Alberta Research Center [3]. Therefore, test results from this pipeline will be used as the data source for computation of EI from Eq. 6. Since in future applications of HCP, all systems should run near optimum conditions, the EI computed in this report will be based on nearly optimum conditions.

Fig. 1 is a reproduction of Figs. 3-73 of [3]; it is for a 10-inch pipeline with capsule shape and dimensions as indicated in the figure. The



D = 10.02 in.	L_t = 20 ft.	ν = 1.0 cs.
k = 0.90	b = 5	ρ = 1.0

Polyken tape covered steel cylinders with Polyken tape bands in steel pipe. Effect of S. G.

Fig. 1 - Energy Loss Along Hydraulic Capsule Pipeline

optimum condition for this pipeline is to use capsules with specific gravity equal to 1.1 approximately, and with capsule speed in the neighborhood of 5 fps. This results in a minimum capsule energy gradient (i.e., head loss per length of pipe) of 0.0050 psi/ft. Suppose for reasons other than saving energy it is desirable to run a 10-inch HCP at a slightly higher speed--say 6 fps. From Fig. 1 the energy gradient is 0.0054 psi/ft. Other pertinent properties of the system are V_c = 5 fps, s = 1.1, k = 0.9, ε = 0.75, α = 1, and v = 1.* For this system, Eq. 6 yields

$$EI = 3.13\times10^4 \times \frac{0.0050\times0.0054}{0.75\times1\times1.1\times0.9^2} = 253 \text{ Btu/TM}$$

The above value of EI was derived solely from pipeline frictional loss; it does not include losses encountered in the pumping process. To get the value of EI at the supply end of the pump, the above value must be divided by pump efficiency. From Professor E. R. Laithwaite's preliminary assessment**, the expected efficiency of electromagnetic pumps (linear motors) for HCP is in the neighborhood of 50%. Therefore, to compute the EI for HCP at the supply end of the pump, the above value should be divided by 0.5, yielding EI = 506 Btu/TM.

Now that the value of EI for a 10-inch HCP is known, how do we predict EI for larger pipes under similar conditions? Approximately, this can be done by assuming the head loss of HCP to be linearly proportional to the head loss of an equivalent ordinary liquid pipeline (i.e. an ordinary liquid pipe flow having the same velocity and pipe diameter).

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* v=1 is a good assumption as long as k is not greater than 0.95.

**Professor Laithwaite is the world's foremost authority on linear motors. His assessment of the expected efficiency of linear motors for pumping capsules in HCP is given in [4].

The head loss for ordinary liquid pipeline may be computed from the Darcy-Weisbach formula as follows:

$$h_f = f \frac{L}{D} \frac{V^2}{2g} \qquad (7)$$

Where f--the resistance factor--may be found from Moody diagram given in standard texts. Assuming water of viscosity 1.2×10^{-5} ft^2/sec flows at 6 fps in a 10-inch steel pipe, the Reynolds number is 4.2×10^5, and the resistance factor is $f=0.0155$. Eq. 7 yields a head loss of 55 ft over a distance of one mile. Since head loss for liquid pipeline is the energy spent in transporting liquid of unit weight over unit distance, it is physically the same as EI. The EI for ordinary liquid pipeline is

$$EI = \left(\frac{2000}{778}\right) h_f = 2.57\ h_f \qquad (8)$$

where the units of EI and h_f are respectively Btu/TM and ft/mile.

From Eq. 8, the EI corresponding to the 55 ft head loss in the 10-inch pipe is 141 Btu/TM. If pump efficiency for ordinary liquid pipeline is assumed to be 80%, the EI for the 10-inch line based on power supplied to the pump must be 176 Btu/TM.

The above procedure may be used to calculate the EI for any liquid pipeline of any diameter and velocity. For instance, for a 12-inch water line with water flowing at 6 fps, the EI based on power supply to the pump calculated in this manner is 143 Btu/TM. Now that the EI of the 12-inch water line is known, the anticipated EI for an equivalent HCP system (i.e., an HCP of 12-inch diameter and 6 fps speed) is

$$\text{EI for 12" HCP} = \frac{\text{EI for 10" HCP}}{\text{EI for equivalent 10" water line}} \times \text{EI for 12" water line}$$

$$= \frac{506}{176} \times 143 = 411 \text{ Btu/TM.}$$

Using the above projection technique, the EI for HCP based on pump energy consumption has been computed for linefill from 70% to 100% and for pipe diameters up to 12 feet. The result is presented in Table 2. The corresponding throughputs may be found from Table 3. The values in Table 3 are computed from Eqs. 3 and 5. Note that 12 feet has been chosen as the upper limit of HCP since at that diameter any cargo that can be transported by truck can be placed inside a capsule.

2. Energy Consumed at HCP Terminals

The bulk of energy needed in the operation of HCP is that used in pumping. Terminal operations (sealing capsules, transporting capsules within terminal buildings, capsule injection, building lighting, heating and air-conditioning, etc.) require much less energy. They can be estimated as follows:

It is expected that after capsules have been filled with cargo, they will be sealed by a spring-loaded compression cap. To compress the cap into position in order to seal each capsule requires an energy equal to:

Energy for Sealing Capsule = Force to compress the spring
x Change of Spring Length.

The force to compress the spring is assumed to be 1,000 lbs which is on the conservative side. The change of spring length (i.e., distance shortened) is assumed to be 3 inches for 1-ft-diameter HCP, and proportionally longer for larger pipe. Thus, for capsules going through a 1-ft pipe, the energy for sealing per capsule is

$$1{,}000 \times \frac{3}{12} = 250 \text{ ft-lb} = 0.321 \text{ Btu}$$

TABLE 2 - EI for HCP Based on Power Consumed by Pumps

Pipe Diameter	EI (Btu/TM)				
	HCP				Equivalent Water Line
	$\alpha = 1.0$	$\alpha = 0.9$	$\alpha = 0.8$	$\alpha = 0.7$	
10"	506	562	633	723	176
1'	411	457	514	587	143
1'6"	253	281	316	361	88
2'	176	196	220	251	61
3'	107	119	134	153	38
4'	78	87	98	111	28
5'	61	68	77	88	21
6'	49	54	61	70	17
7'	40	44	50	57	14
8'	34	38	43	49	12
9'	29	33	37	42	10
10'	28	31	35	40	9
11'	27	30	33	38	9
12'	24	27	30	34	8

Note: $V_c = V = 6$ fps, $k = 0.9$, $s = 1.1$, $\epsilon = 0.75$, pump efficiency for HCP = 0.5, pump efficiency for water line = 0.8).

TABLE 3 - HCP Throughput (100% Linefill)

Pipe Diameter	Capsule Throughput			Cargo Throughput			Water Throughput
	No. Per Minute	No. Per Hour	No. Per day	Tons Per Second	Tons Per Day	Tons Per Year*	cfs
10"	96	5,760	$1.38\text{x}10^5$	0.068	$5.89\text{x}10^3$	$2.12\text{x}10^6$	0.62
1'	80	4,800	$1.15\text{x}10^5$	0.098	$8.48\text{x}10^3$	$3.05\text{x}10^6$	0.90
1'6"	53	3,200	$7.68\text{x}10^4$	0.221	$1.91\text{x}10^4$	$6.87\text{x}10^6$	2.01
2'	40	2,400	$5.76\text{x}10^4$	0.393	$3.39\text{x}10^4$	$1.22\text{x}10^7$	3.58
3'	27	1,600	$3.84\text{x}10^4$	0.884	$7.64\text{x}10^4$	$2.75\text{x}10^7$	8.06
4'	20	1,200	$2.88\text{x}10^4$	1.571	$1.36\text{x}10^5$	$4.89\text{x}10^7$	14.3
5'	16	960	$2.30\text{x}10^4$	2.46	$2.12\text{x}10^5$	$7.64\text{x}10^7$	22.4
6'	13	800	$1.92\text{x}10^4$	3.54	$3.05\text{x}10^5$	$1.10\text{x}10^8$	32.2
7'	11	685	$1.65\text{x}10^4$	4.81	$4.16\text{x}10^5$	$1.50\text{x}10^8$	43.9
8'	10	600	$1.44\text{x}10^4$	6.28	$5.43\text{x}10^5$	$1.95\text{x}10^8$	57.3
9'	8.9	533	$1.28\text{x}10^4$	7.95	$6.87\text{x}10^5$	$2.47\text{x}10^8$	72.5
10'	8.0	480	$1.15\text{x}10^4$	9.82	$8.48\text{x}10^5$	$3.05\text{x}10^8$	89.5
11'	7.3	436	$1.05\text{x}10^4$	11.9	$1.03\text{x}10^6$	$3.70\text{x}10^8$	108
12'	6.7	400	$9.60\text{x}10^3$	14.1	$1.22\text{x}10^6$	$4.40\text{x}10^8$	129

Note: $V_c = V = 6$ fps, $k = 0.9$, $s = 1.1$, $\epsilon = 0.75$, $b = 5.0$.

*Assume the pipeline is operational 360 days per year.

Table 3 shows that for $\alpha=1.0$, there are 1.15×10^5 capsules entering the pipe every day. If $\alpha=0.7$ (i.e., 70% line fill), the number is reduced to 8.05×10^4 capsules/day. To seal these capsules will require an energy of $0.321\times8.05\times10^4 = 2.58\times10^4$ Btu/day.

The energy required to move each capsule within terminals is assumed to be the same as the work performed by lifting each capsule for a height of 100 ft. For the 1-ft HCP at $\alpha=0.7$, this requires a total work of 2.9×10^6 Btu/day.

The energy needed for lighting, heating and air-conditioning the terminals is assumed to be 3 watts/ft^2. Assuming the area of each terminal building is 100 ftx100 ft, the total energy needed to light, heat or air-condition the two terminals of each HCP for one day is $3\times2\times100\times100\times24 = 1.44\times10^6$ watts-hr which is equivalent to

$$1.44\times10^6\times\cdot\frac{2.66\times10^3}{774} = 4.93\times10^6 \text{ Btu/day}$$

From the above, the total energy consumed at terminals is

$$2.58\times10^4 + 2.9\times10^6 + 4.93\times10^6 = 7.86\times10^6 \text{ Btu/day}$$

The above results are listed in Table 4, together with results computed for pipes up to 12-ft diameter.

To convert the results in Table 4 to EI, pipe length must be specified. For instance, for a 1-ft HCP, Table 4 gives the total energy consumed at the terminals as 7.9×10^6 Btu/day. The throughput at 70% linefill is, from Table 3, $0.7\times8.48\times10^3 = 5.94\times10^3$ tons/day. If the pipeline is 50 miles long, the EI for terminals is

TABLE 4 - Estimated Energy Consumption at HCP Terminals (70% Linefill)

Pipe Diameter	Energy Consumed (Btu/day)			
	Capsule Sealing	Capsule Transport Within Terminals	Lighting, Heating and Air-Conditioning	Total
10"	2.6×10^4	1.4×10^6	4.9×10^6	6.3×10^6
1'	2.6×10^4	2.0×10^6	4.9×10^6	7.9×10^6
1'6"	2.6×10^4	4.6×10^6	4.9×10^6	9.5×10^6
2'	2.6×10^4	8.4×10^6	4.9×10^6	1.3×10^7
3'	2.6×10^4	1.8×10^7	4.9×10^6	2.3×10^7
4'	2.6×10^4	3.3×10^7	4.9×10^6	3.8×10^7
5'	2.6×10^4	5.1×10^7	4.9×10^6	5.6×10^7
6'	2.6×10^4	7.7×10^7	4.9×10^6	8.2×10^7
7'	2.6×10^4	9.8×10^7	4.9×10^6	1.0×10^8
8'	2.6×10^4	1.3×10^8	4.9×10^6	1.3×10^8
9'	2.6×10^4	1.7×10^8	4.9×10^6	1.7×10^8
10'	2.6×10^4	2.0×10^8	4.9×10^6	2.0×10^8
11'	2.6×10^4	2.5×10^8	4.9×10^6	2.5×10^8
12'	2.6×10^4	2.9×10^8	4.9×10^6	2.9×10^8

$$\frac{7.9\times10^{6}}{5.94\times10^{3}\times50} = 26.6 \text{ Btu/TM}$$

Using the above approach, the values in Table 4 were transformed to EI as given in Table 5.

3. EI for HCP System

Adding the EI for pumping to that for terminal operation gives the total EI for the HCP system. For instance, from Tables 2 and 5, the total EI for a 100-mile long one-foot diameter HCP system at 70% linefill is 587+13 = 600 Btu/TM. This is the EI based on the electrical power supplied to the HCP system. Since power generation from coal and subsequent distribution of electricity have a combined efficiency--the electric grid efficiency--of approximately 22%, the EI based on the energy released from coal in power generation is 600/0.22 = 2,727 Btu/TM. Using this approach, the EI for HCP based on the energy released from coal was computed under various conditions, and the results were summarized in Table 6. These values of EI will be considered as the basic EI values for HCP. They will be compared to corresponding values for slurry pipeline in the next section.

B. Slurry Pipeline

Slurry pipeline has been used with success to transport minerals over long distances in many parts of the world. An existing slurry pipeline is the Black Mesa line in the U.S. to transport coal. In slurry pipelining of coal, the coal is pulverized first, and then mixed with water to form the slurry which contains approximately 50% water and 50% coal by weight. Then the slurry is pumped through pipeline at a speed in the neighborhood of 6

TABLE 5 - EI Based on Energy Consumed at HCP Terminals (70% Linefill)

Pipe Diameter	EI (Btu/TM)						
	Pipe Length						
	50 Miles	100 Miles	200 Miles	300 Miles	500 Miles	700 Miles	1,000 Miles
10"	31	15	8	5	3	2	2
1'	27	13	7	4	3	2	1
1'6"	14	7	4	2	1	1	1
2'	10	6	3	2	1	1	1
3'	9	4	2	1	1	1	0
4'	8	4	2	1	1	1	0
5'	8	4	2	1	1	1	0
6'	8	4	2	1	1	1	0
7'	7	3	2	1	1	0	0
8'	7	3	2	1	1	0	0
9'	7	3	2	1	1	0	0
10'	7	3	2	1	1	0	0
11'	7	3	2	1	1	0	0
12'	7	3	2	1	1	0	0

TABLE 6 - Basic EI Values for HCP* (70% Linefill)

Pipe Diameter	EI (Btu/TM)							
	Pipe Length							
	50 Miles	100 Miles	200 Miles	300 Miles	500 Miles	700 Miles	1,000 Miles	∞ Miles
10"	3,430	3,350	3,320	3,310	3,300	3,290	3,290	3,290
1'	2,790	2,730	2,700	2,690	2,680	2,675	2,670	2,670
1'6"	1,700	1,670	1,660	1,650	1,645	1,645	1,645	1,640
2'	1,190	1,170	1,155	1,150	1,145	1,145	1,145	1,140
3'	736	714	705	700	700	700	695	695
4'	541	523	514	509	509	509	505	505
5'	436	418	409	405	405	405	400	400
6'	355	336	327	323	323	323	318	318
7'	291	273	268	264	264	259	259	259
8'	255	236	232	227	227	223	223	223
9'	223	205	200	195	195	191	191	191
10'	214	195	191	186	186	182	182	182
11'	205	186	182	177	177	173	173	173
12'	186	168	164	159	159	155	155	155

*The basic EI values are those based on the energy released from coal in generating the electricity needed to power the HCP system.

Note: $V_c = V = 6$ fps, $k = 0.9$, $s = 1.1$, $\epsilon = 0.75$, pump efficiency for HCP = 0.5, electric grid efficiency = 0.22

fps. An analysis of the energy consumption of coal slurry pipeline now follows:

1. Frictional Loss along Slurry Pipeline and Energy for Pumping

How to compute slurry pipeline frictional loss can best be illustrated through an example, as given below.

Consider a coal slurry pipeline of 10" diameter and 6 ft/sec velocity. From Mitchell [5], the specific gravity of coal varies from 1.28 to 1.70. A common value used for the specific gravity of coal is 1.4, same as that used herein. Since slurry is assumed to contain 50% solid by weight, the specific gravity and the density of the slurry mixture should be respectively

$$s_m = \frac{0.5\text{x}1.4 + 0.5\text{x}1.0}{1} = 1.2, \quad \text{and}$$

$$\rho_m = 1.2\text{x}1.94 = 2.33 \text{ slug/ft}^3 .$$

As discussed in Govier and Aziz [6], the slurry behaves like Bingham plastic fluid. The coefficient of rigidity* of coal slurry with 50% solids by weight is approximately ζ=28 centipoises. In English unit, this is $5.84\text{x}10^{-4}$ lb-sec/ft^2.

Knowing the values of the slurry density ρ_m, and the coefficient of rigidity, ζ, the Reynolds number of the slurry pipe flow is

$$(\text{Re})_{\text{slurry}} = \frac{DV\rho_m}{\zeta} = \frac{\frac{10}{12} \times 6 \times 2.33}{5.85 \times 10^{-4}} = 2.0 \times 10^4$$

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*Coefficient of rigidity, ζ, for slurry, is the counterpart of the dynamic viscosity, μ, of Newtonian fluid.

As explained by Zandi in [3], this slurry Reynolds number may be used in standard fraction factor Reynolds number charts, such as the Moody or the Fanning diagram, to determine head loss. With Re=2.0 x 10^4 and $\epsilon/D = 0.00018$ (ϵ = .00015 for steel pipe), the resistance factor from the Moody diagram is f = 0.026. Therefore, the head loss per mile is

$$h_f = f \frac{L}{D} \frac{V^2}{2g} = 0.026 \frac{5280}{10/12} \times \frac{36}{64.4} = 92.1 \text{ ft/mi}$$

The corresponding pressure drop is

$$\Delta p = 1.2 \times 62.4 \times 92.1 = 6900 \text{ psf}$$

The power used per mile is

$$P = Q_b \Delta p = 3.27 \times 6900 = 22{,}600 \text{ ft-lb/sec-mile} = 29 \text{ Btu/sec-mile}$$

The solid throughput is

$$W = Q_b \gamma_s \times 50\% = 3.27 \times 62.4 \times 1.2 \times 0.5 = 122 \text{ lbs/sec}$$
$$= 0.0612 \text{ tons/sec.}$$

Thus, the EI of the slurry pipeline caused by frictional loss is

$$EI = \frac{P}{W} = \frac{29}{0.0612} = 474 \text{ Btu/TM.}$$

The above value of EI is that at the pipeline level. Assuming slurry pumps are 70% efficient, the EI at the pump level is 474/0.7 = 677 Btu/TM. Following the above approach, the values of EI for slurry pipeline at diameters 1', 1'6", 2', and 3' were computed and listed in Table 7. No attempt

TABLE 7 - Computation of EI from Frictional Loss Along Slurry Pipeline

Pipe Diameter, D (inch)	Pipe Area A (ft^2)	Bulk Discharge Q_b (cfs)	Reynolds No., Re (10^4)	Relative Roughness ϵ/D (10^{-5})	Friction Factor, f (10^{-3})	Headloss h_f (ft/mile)	Pressure Drop Δp (psf)	Power Consumed P (Btu/sec. mi)	EI(Btu/TM)		Throughput of Coal (ton/sec)
									Pipeline level	Pump Level	
10	0.545	3.27	2.0	18	26	92	6,900	29	474	677	0.061
12	0.785	4.71	2.4	15	25	74	5,540	34	386	551	0.088
18	1.767	10.6	3.6	10	23	45	3,370	46	232	331	0.198
24	3.142	18.85	4.8	75	23	31	2,320	56	157	224	0.353
36	7.069	42.4	7.2	50	20	19	1,420	78	998	140	0.794

Note: V = 6 fps, steel pipe, 50% coal by weight, specific gravity of coal = 1.4, specific gravity of slurry mixture = 1.2, slurry coefficient of rigidity = 5.85×10^{-4} lb-sec/ft^2, slurry pump efficiency = 70%.

was made to calculate the EI for slurry pipelines with diameter greater than 3 feet because no coal slurry pipeline that large will be needed in the future.

2. Energy Consumed at Slurry Pipeline Terminals

The energy consumed at slurry pipeline terminals may be itemized as follows:

Dewatering Coal

A large amount of electrical energy is used in dewatering the coal coming out from slurry pipeline. From information extracted from [7], the electricity consumed for this purpose is approximately 9.3 Kw-Hr or 32,000 Btu per ton of coal extracted. According to Banks [8], the electrical energy consumed for dewatering coal is $6.88\times10^5\times0.22 = 1.51\times10^5$ Btu/ton of coal for the Black Mesa Pipeline (old technology), and $2.01\times10^5\times0.22 = 4.42\times10^4$ Btu/ton of coal for the ETSI Pipeline (new technology). This means the value of 32,000 Btu/ton should be considered as a minimum.

Slurry Preparation

Slurry preparation (pulverizing coal) also requires a large amount of electrical energy. From [7], the energy used for this purpose is approximately 7.8 Kw-Hr or 2.7×10^4 Btu per ton of coal. Some slurry pipeline experts contend that pulverizing coal is necessary for burning the coal at power plants, and hence the energy used for pulverizing coal should not be charged to slurry pipeline. Investigation shows this argument is only partially true. Not all power plants burn pulverized coal, and for those that do, the coal particles do not have to be as fine as that for slurry pipeline operation. Therefore, at least a large portion of the energy used

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*Slurry pipeline from Wyoming to Arkansas proposed by the Energy Transportation Systems, Inc. (ETSI).

in pulverizing coal should be charged to slurry pipeline Somewhat arbitrarily, two-thirds of the energy consumed in pulverizing coal will be charged to slurry pipeline in this analysis. This means the value of $2/3 \times 2.7 \times 10^4 = 1.8 \times 10^4$ Btu per ton of coal will be used for slurry preparation.

Water Supply

Slurry pipeline requires a constant supply of water which may or may not be available from a nearby source Owing to the fact that most proposed coal slurry pipelines in the U.S. are for transporting coal from arid states such as Wyoming and Utah to other parts of the nation, water supply will be a major problem in the development of these pipelines. Instead of getting water from distant places, these pipelines may use local ground water which, in those states, may exist several thousand feet below ground surface.

Suppose the water supply must come from a ground water table 2,500 ft below ground. To lift it 2,500 ft with a pump 80% efficient will require a minimum energy of·

$$\frac{2500 \times 2000}{778 \times 0.8} = 8{,}033 \text{ Btu/ton of water.}$$

Since the coal-water ratio of slurry is 1 to 1 by weight, this means the slurry pipeline will consume 8,033 Btu of electrical energy for every ton of coal transported. This figure, when divided by an electric grid efficiency of 22%, becomes very close to the 36,000 Btu/ton of coal calculated by Banks [7] for the Black Mesa line--the only slurry pipeline now in use in the U.S.

Lighting, Heating, Air-Conditioning, Etc.

Lighting, heating or air-conditioning of terminal buildings of slurry pipelines should be about the same as for HCP. This means the approximate figure of 5×10^6 Btu/day used for HCP will be applicable to slurry pipeline.

However, since this is a small amount as compared to the energy used in slurry preparation, dewatering, and water supply, it can be neglected without noticeable error.

Summary of Energy Consumed at Slurry Pipeline Terminals

The above shows that the energy consumed at slurry pipeline terminals, due primarily to slurry preparation and dewatering and water supply, is approximately equal to 32,000 + 18,000 + 8,000 = 58,000 Btu/ton of coal. Dividing this figure by the length of pipeline in miles yields the EI in Btu/TM as shown in Table 8.

TABLE 8 - EI Based on Energy Consumed at Slurry Pipeline Terminals

Pipe Length (Miles)	50	100	200	300	500	700	1,000	∞
EI (Btu/TM)	1,160	580	290	193	116	83	58	0

Comparing values of EI in Table 8 with those in Table 7 indicates that the EI for slurry pipeline terminal may be greater than the EI for frictional loss along slurry pipelines when the pipeline is short and when the pipe diameter is large.

3. EI for Slurry Pipeline System

Adding the corresponding values of EI in Tables 7 and 8, and dividing each number by the electric grid efficiency of 22%, yields the values of EI for entire slurry pipeline systems based on the energy released from coal in generating the electricity needed to power the slurry pipeline systems.

These values of EI, termed "basic EI for slurry pipeline," are summarized in Table 9.

C. Comparison of HCP with Slurry Pipeline

Since both HCP and slurry pipelines use mainly electrical energy to power their systems, a direct comparison of the basic values of EI for slurry pipelines (given in Table 9) and HCP (given in Table 6) is meaningful. To facilitate comparison, results in Tables 9 and 6, for pipe diameter from 10 inches to 3 feet, are summarized in Table 10. It can be seen from Table 10 that for any pipeline less than one thousand miles long, HCP consumes less energy than slurry pipeline. The shorter the pipeline is, the greater the advantage of HCP over slurry pipeline. For instance, for a 3-ft pipe 50 miles long, HCP uses only about one-eighth the energy used by slurry pipeline.

D. Comparison of HCP with Trucks, Trains, Waterways, Air-Freight, and PCP (Pneumatic Capsule Pipeline)

Table 1 lists the average value of EI for air-freight as 37,000 Btu/TM which is much higher than the EI for HCP or any other mode of ground or water transportation system. However, a comparison of the EI of HCP with air transport would be entirely meaningless because air transport is needed for speedy delivery of special cargoes. The two modes of transport belong to different market places.

A comparison of HCP with PCP is also meaningless because, as described by Liu [9], PCP is practical only for distances much shorter than that practical for HCP. Again the two belong to different markets.

TABLE 9 - Basic EI Values for Slurry Pipeline*

Pipe Diameter	EI (Btu/TM)							
	Pipe Length							
	50 Miles	100 Miles	200 Miles	300 Miles	500 Miles	700 Miles	1,000 Miles	∞ Miles
10"	8,350	5,710	4,400	3,950	3,600	3,450	3,340	3,080
1'	7,780	5,140	3,820	3,380	3,030	2,880	2,770	2,500
1'6"	6,780	4,140	2,820	2,380	2,030	1,880	1,770	1,500
2'	6,290	3,650	2,340	1,900	1,550	1,400	1,280	1,020
3'	5,810	3,270	1,950	1,510	1,160	1,010	900	636

*The basic EI values are those based on the energy released from coal in generating the electricity needed to power the slurry pipeline system.

Note: V = 6 fps, steel pipe, 50% coal by weight, specific gravity of coal = 1.4, specific gravity of slurry mixture = 1.2, slurry coefficient of rigidity = 5.85×10^{-4} lb-sec/ft^2, slurry pump efficiency = 70%, electric grid efficiency = 22%.

TABLE 10 - Comparison of Basic EI Values between Slurry Pipeline and HCP

Pipe Diameter	Type of Pipe	EI (Btu/TM)							
		Pipe Length							
		50 Miles	100 Miles	200 Miles	300 Miles	500 Miles	700 Miles	1,000 Miles	∞ Miles
10"	HCP	3,430	3,350	3,320	3,310	3,300	3,290	3,290	3,290
	Slurry	8,350	5,710	4,400	3,950	3,600	3,450	3,340	3,080
1'	HCP	2,790	2,730	2,700	2,690	2,680	2,675	2,670	2,670
	Slurry	7,780	5,140	3,820	3,380	3,030	2,880	2,770	2,500
1'6"	HCP	1,700	1,670	1,660	1,650	1,645	1,645	1,645	1,640
	Slurry	6,780	4,140	2,820	2,380	2,030	1,880	1,770	1,500
2'	HCP	1,190	1,170	1,155	1,150	1,145	1,145	1,145	1,140
	Slurry	6,290	3,650	2,340	1,900	1,550	1,400	1,280	1,020
3'	HCP	736	714	705	700	700	700	695	695
	Slurry	5,910	3,270	1,950	1,510	1,160	1,010	900	636

Note: For HCP: Linefill = 70%, k = 0.9, s = 1.1, ε = 0.75, pump efficiency = 50%.

For Slurry: 50% coal by weight, specific gravity of coal = 1.4, pump efficiency = 70%.

For both systems: V = 6 fps, steel pipe, electric grid efficiency = 22%.

Most types of cargoes normally transported by trucks, trains and waterways can be transported by HCP. Therefore, it makes sense to compare HCP with these three modes of transports. However, just to compare EI is not good enough because while the EI for HCP is based on the energy derived from coal, the EI's for trucks, trains and waterways are those based on the energy derived from oil (diesel fuel, more specifically). To compare one Btu from coal to one Btu from diesel is like comparing one pound of oranges with one pound of grapes: they have different economic values. For this reason, instead of comparing the EI of HCP with that of truck, train, and waterways, the values of ECI should be compared, as discussed previously.

Assuming the prices of coal and diesel to be respectively \$30.00/ton and \$0.50/gal, the prices of energy derived from coal and diesel become respectively 1.2×10^{-6} \$/Btu and 3.6×10^{-6} \$/Btu. This shows the price of energy from diesel is approximately three times that from coal.

The ECI of HCP can now be obtained simply by multiplying the values of EI given in Table 6 by the price of energy from coal which is 1.2×10^{-6} \$/Btu. The results are listed in Table 11. On the other hand, based on the average values of EI listed in Table 1 and the price of energy from diesel which is 3.6×10^{-6} \$/Btu, the ECI for truck, train and waterways is respectively 8.28, 2.45 and 1.94 mills/TM.

Comparison of the values of ECI listed above for truck, train and waterways with those given in Table 11 for HCP indicates that even for HCP as small as 10 inches in diameter, one gets twice as much fuel economy by using HCP than trucks. For HCP greater than 3 feet in diameter, the advantage in fuel economy over trucks is more than ten times. This shows the

TABLE 11 - ECI Values for HCP (70% Linefill)

Pipe Diameter	ECI (Mills/TM)							
	Pipe Length							
	50 Miles	100 Miles	200 Miles	300 Miles	500 Miles	700 Miles	1,000 Miles	∞ Miles
10"	4.1	4.0	4.0	4.0	4.0	3.9	3.9	3.9
1'	3.3	3.3	3.2	3.2	3.2	3.2	3.2	3.2
1'6"	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
2'	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
3'	0.88	0.86	0.85	0.84	0.84	0.84	0.83	0.83
4'	0.65	0.63	0.62	0.61	0.61	0.61	0.61	0.61
5'	0.52	0.50	0.49	0.49	0.49	0.49	0.48	0.48
6'	0.43	0.40	0.39	0.39	0.39	0.39	0.38	0.38
7'	0.35	0.33	0.32	0.32	0.32	0.31	0.31	0.31
8'	0.31	0.28	0.28	0.27	0.27	0.27	0.27	0.27
9'	0.27	0.25	0.24	0.23	0.23	0.23	0.23	0.23
10'	0.26	0.23	0.23	0.22	0.22	0.22	0.22	0.22
11'	0.25	0.22	0.22	0.21	0.21	0.21	0.21	0.21
12'	0.22	0.20	0.20	0.19	0.19	0.19	0.19	0.19

Note: $V_c = V = 6$ fps $k = 0.9$, $s = 1.1$, $\varepsilon = 0.75$,

pump efficiency of HCP = 0.5, electric grid efficiency = 0.22,

price of energy from coal = 1.2×10^{-3} mill/Btu.

tremendous advantage of HCP over trucks as far as fuel economy goes.

Comparison of HCP with train shows that HCP gives better fuel economy than train when the pipe diameter is larger than one foot approximately. When the pipe diameter is greater than 5 feet, HCP gives more than five times better fuel economy than train. Finally, HCP also gives better fuel economy than waterway when the pipe diameter is greater than about 1.5 feet.

E. Comments on Comparisons

The foregoing comparisons of HCP with other modes of freight transport must be viewed in proper perspective. The following important facts must be borne in mind:

1. The analysis of the frictional loss of HCP was based on optimum conditions. If a system is not operating under optimum conditions, either due to poor design or poor management, the system can consume much more energy. On the other hand, future research may find ways to reduce frictional loss along HCP, either through the use of drag reducing chemicals such as polymers, through improved capsule design, or through other means. If this happens, further improvement of the energy efficiency of HCP will be realized.

2. The assumed efficiency of HCP pump is 50%. Although this is what experts in linear motor feel can be accomplished, it should be emphasized that to date no experiment has been conducted to determine the efficiency and the characteristics of HCP pumps. Research in this area is badly needed.

3. The values of EI and ECI for HCP was computed from the assumption of 70% linefill. Although there is no technical difficulty to achieve this degree of linefill, questions remain whether there is enough cargo to attain 70% linefill. In the case of HCP specifically built for coal transportation,

there should be no problem in getting more than 70% linefill through proper design. A deliberate under-design of the pipeline may even give the system a linefill close to 100%. However, in the case of HCP built for intercity transport of general cargoes, the system may have to be over-designed so that the pipeline will be large enough for transporting large size cargoes. In such a case, linefill may be much less than 70%. Of course, no HCP should be built with such a low linefill that makes the system uneconomical. Although what is an economical linefill rate cannot be determined in general, it can be calculated in the design of specific systems.

4. The values of EI and ECI were computed for two-way freight transport. This will be the case for intercity transport of general cargoes. However, for HCP built specifically for transporting coal, the return pipeline may be carrying only empty capsules. When this happens, the values of EI for HCP listed in Table 10 should be doubled. Although this decreases considerably the competitiveness of HCP over slurry pipeline, at distances shorter than 100 miles HCP still uses less energy than slurry pipeline. Moreover, the EI for slurry pipeline was computed based on the assumption of availability of water from local sources. This is not necessarily true for Western coal. For instance, in the case of the proposed Wyoming-to-Arkansas coal slurry pipeline, strong opposition has been encountered in planning to use local water [7]. An alternative is to pipe water all the way back to Wyoming from Arkansas. If that must be done, the EI values for slurry pipeline in Table 10 also must be increased.

Furthermore, even for HCP designed primarily for transporting coal, through proper planning it may be possible to use at least some returning capsules to transport cargoes. If no other cargo can be transported, one could at least use the returning capsules to carry fly ash or solid waste to fill mine pits. This would solve both the solid waste disposal problem and the problem of restoring the contours of mine fields--two problems of increasing concern to the nation. Of course, study is needed to determine the possibility of water pollution by filling mine pits with fly ash or solid waste.

5. The values of ECI computed are based on current prices of coal and petroleum. Based on these prices, it was found that one Btu derived from petroleum (diesel, more specifically) is approximately three times as expensive as one Btu derived from coal. This ratio actually varies somewhat with geographical locations, due to the fact that the price of coal varies somewhat with location; less variation of price with location exists for petroleum products. This ratio of three is also expected to change in the future. However, due to the fact that coal is a natural resource much more abundant than oil, the price of petroleum products is expected to increase faster than that of coal. This means in the future one Btu from diesel may become more than three times expensive than from coal. Such a trend further enhances the attractiveness of HCP.

V. ENERGY CONSERVATION POTENTIAL OF HCP

The foregoing analyses showed that, under a wide range of conditions, HCP is more energy efficient than slurry pipeline, trucks, trains and even waterways.

The greatest contribution HCP can make in the future in energy conservation is when competing with trucks for market. According to [10], in the U.S. in 1974, trucks consumed approximately 22% of the fuel used in transportation. This amounts to $4.3\text{x}10^{15}$ Btu per year or $3.1\text{x}10^{10}$ gallons of diesel per year. If eventually HCP can cut in 10% of the market of trucks, it would mean the saving of 3 billion gallons of oil per year--a substantial decrease in U.S. reliance on oil. Of course, more coal or uranium must be consumed to generate the additional electrical energy to power the HCP.

Even if one assumes the electricity to power HCP is generated from oil, there is still a considerable saving in oil because the EI for large systems of HCP (see Table 10) is less than one-half the value of EI for trucks (see Table 1). This means a saving of more than one billion gallons of oil per year could be achieved if 10% of the truck freight in the U.S. is shifted to HCP, even if in doing so the electricity to power HCP had to come from oil-fired power plants.

Of course, substantial energy saving may also be accomplished by the replacement of a portion of the market of railroad, waterway, and slurry pipeline by HCP. For instance, if instead of building a slurry pipeline 2 feet in diameter and 100 miles long, one uses an HCP of the same size and length, Table 10 indicates that EI will be reduced from 3,650 to 1,170 Btu/TM--a reduction of about 2,500 Btu/TM. From Table 7, the throughput of coal for the system is 0.353 ton/sec. This means the saving in Btu's per year for this pipeline alone will be approximately

$$2{,}500 \times 0.353 \times 100 \times 360 \times 24 \times 3600 = 2.7 \times 10^{12} \text{ Btu per year.}$$

This is equivalent to the saving of 100 thousand tons of coal per year, or 20 million gallons of oil per year. The saving in money from fuel cost in

40 years--the expected life span of the pipeline system--is over 100 million dollars. Even if one assumes the return pipeline of this HCP system cannot be utilized and the slurry pipeline has a nearby water source, the saving in money for this HCP system would still be more than 50 million dollars.

APPENDIX 1 - REFERENCES

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APPENDIX 2 - SYMBOLS

A = pipe area ($\pi D^2/4$);

A_c = capsule area ($\pi D_c^2/4$);

b = capsule length ratio (L_c/D_c);

D = pipe diameter (I.D.);

D_c = capsule diameter (O.D.);

e = pipe roughness (0.00015 ft for steel);

EI = energy intensiveness;

ECI = energy cost intensiveness;

f = Darcy-Weisbach resistance factor;

g = gravitational acceleration (32.2 ft/sec^2);

h_f = head loss along pipeline;

HCP = hydraulic capsule (container) pipeline;

k = capsule diameter ratio (D_c/D);

L = pipe length;

L_c = capsule length;

n = number of capsules going through pipe per second;

P = power consumed along unit length of pipeline;

Δp = pressure drop along pipeline;

PCP = pneumatic capsule (container) pipeline;

Q = discharge of water, in cfs;

Q_b = bulk discharge (including both water and solids or capsules), in cfs;

Q_c = discharge of capsules, in cfs;

Re = Reynolds number;

s = specific gravity of loaded capsules;

s_m = specific gravity of slurry mixture;

S_f = frictional slope or energy gradient (i.e., head loss per unit length of pipe);

V = velocity of water in pipe (Q/A);

V_b = bulk velocity (including both water and solids or capsules);

V_c = capsule velocity;

v = capsule velocity ratio (V_c/V_b);

W = cargo throughput (i.e., weight of cargo transported in unit time);

α = linefill (i.e., length of pipe filled with capsules divided by total length of pipe);

ϵ = capsule load factor (i.e., weight of cargo inside a capsule divided by weight of filled capsules);

γ = specific weight of fluid (62.4 lbs/ft^3 for water);

ρ_m = density of slurry mixture;

and

ζ = coefficient of rigidity of slurry mixture.

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