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An Advanced Electromagnetic Capsule Pipeline System for Conveying Minerals and Mine Wastes

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ABSTRACT

Under the sponsorship of the U.S. Department of Energy (DOE), a project has been completed in 2005, which studied the use of a special pneumatic capsule pipeline (PCP) system, driven by linear induction motor (LIM), for transporting minerals and/or mine wastes. In this study, the pipeline is a rectangular conduit of 1m x 1m cross section. The capsules are similar to railroad cars running on small rails imbedded in the conduit. A LIM is placed in the entrance region of the conduit to transfer power electromagnetically from the LIM to the capsules. The capsules going through the LIM, propelled by the electromagnetic field generated by the LIM, move faster than the air and hence impart energy into the airflow through the conduit, which in turn pushes the capsules in the conduit forward. When the conduit is long (say longer than 10 km), additional LIMs may be placed along the conduit to serve as booster pumps.

An advantage of using LIMs instead of blowers as used in ordinary PCPs, such as those used in Japan, is that capsules can pass through the LIMs unhindered. This makes it possible to use booster pumps for long pipelines (conduits). It also enables the PCP system to achieve a much higher capsule flow rate (which is the number of capsules passing through the pipe per second), and a much larger cargo throughput (which is the tonnes of cargoes transported per second), than that of ordinary systems using blowers. Having a large throughput reduces the cost of transporting each tonne of cargo, thereby enhancing the cost-effectiveness of the PCP system.

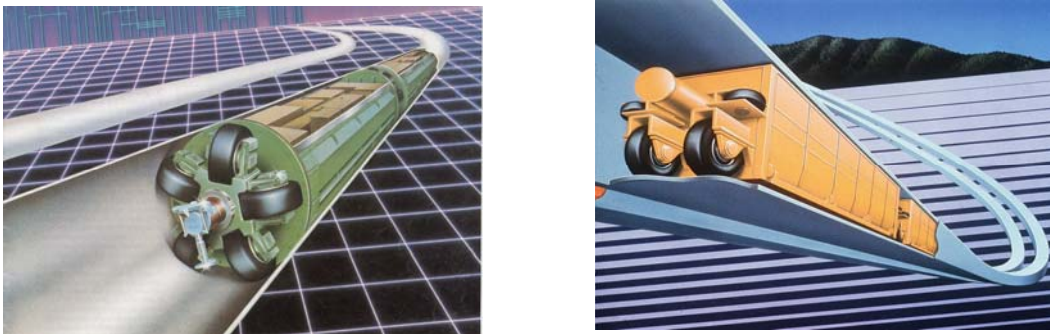
There are several advantages of using capsules with steel wheels running on steel rails in the conduit, including: (1) the contact friction is only about one-fifth of that using rubber tires, thereby conserving energy, (2) the capsules can run at a much higher speed than those using rubber tires without damage due to heat accumulation, and (3) rails make control of capsule motion, such as breaking and switching, easy.

The advanced PCP system designed and analyzed in this DOE study combines the advantages of using LIM with the advantages of using steel wheels running on rails, resulting in a super efficient system that can have throughputs an order of magnitude greater than that of conventional PCP systems driven by blowers. It is especially suitable for use in cases that require large throughputs and long transportation distances.

The study completed the design of the advanced PCP system, and analyzed the system behavior under various conditions. It also conducted a detailed cost analysis of the system under a wide range of operational conditions. The cost analysis showed that the system with twin conduits, one for cargo delivery and the other for the return of empty capsules, is most cost effective for throughputs greater than 10 MTY (million tonnes per year). For smaller throughputs, use of a single conduit for both delivery and return is more cost effective. This paper presents findings and conclusions of this recently completed project.

1. Introduction

Pneumatic capsule pipeline (PCP) is the modern version of the century old technology of “tube transport” or “pneumatic tubes”, for transporting cargoes [1-3]. While the old tube transport systems used small-bore pipes or tubes of less than 100 mm (1 ft) in diameter, and used capsules without wheels to contain and transport the cargo through the pipe or tube, the new PCP technology uses large diameter pipes or rectangular conduits, and large capsules with wheels rolling through pipes or conduits driven by air. Japan is the country where PCP has been used most successfully [4-6]. The Japanese used PCPs of approximately 1 m diameter pipe, and 1m x 1m cross-section of rectangular conduits. Each capsule carries 1 to 2 tonnes (metric tons) of cargo. Figure 1 shows the two types of PCPs used in Japan – circular and rectangular types. They were used successfully for mining, for transporting raw materials to modern steel plants and cement plants, for construction of tunnels and highways, and for solid waste disposal. Detailed discussions of the use of PCPs in Japan are given in [7].



(a) Round (circular) PCP

(b) Rectangular or square PCP

Figure 1. Pneumatic capsule pipeline (PCP) systems developed by and Used in Japan
(Courtesy of Sumitomo Metal Industries, Ltd.)

Notwithstanding the success in using PCPs in Japan in recent years, the use of the technology has been limited throughout the world because the current system often could not compete with trucks and trains in terms of flexibility and low cost, and because most transportation providers do not know how to use or consider this new technology, in spite of the enormous environmental and safety benefits of using PCP instead of truck. For instance, PCP does not pollute air and does not cause traffic jam and accidents on highways as trucks do. In the limited use of PCP in Japan, in each case a careful comparison of alternative transportation means were studied before PCP was selected, based not only on economics but also on environmental and safety considerations.

To enhance the attractiveness of PCP so that it will be used more widely, the cost-effectiveness of PCP relative to other freight transport modes much be improved. This research seeks to improve the cost-effectiveness of PCP in two ways: (1) by using linear induction motor (LIM) instead of blowers (fans) to drive the system, and (2) using capsules with steel wheels that run on rails inside the PCP conduit.

2. Advantages of Using LIM in PCP

LIM is the same technology used for the propulsion of magnetically-levitated high-speed trains, for accelerating and stopping roller coasters, and for many other existing commercial applications in which a large linear driving force is needed to propel vehicles or move objects.

The advantage of using LIM instead of blowers to propel capsules through a conduit is that the LIM is a non-intrusive pump located at the inlet of the conduit. Capsules can move through the LIM unhindered, deriving the driving force from the electromagnetic field of the LIM. With small clearance between the LIM and the capsules moving through it, the capsules not only accelerate but also behave as a piston pump, pushing the air through the entire length of the conduit, which propels the capsules in the entire length of the conduit. Thus, the new system driven by LIM combines the advantage of LIM with the advantage of pneumatic conveying. It makes continuous injection of capsules into the pipe possible, which not only simplifies the pipeline operation but also greatly increases the capsule linefill and cargo throughput. Note that *linefill* is the total length of the capsules inside a pipe divided by the length of the pipe. For example, a 20% linefill means that only 20% of the pipe length is occupied by capsules; the remaining 80% of the pipe length is empty or unused. *Throughput* is the tonnage of cargo transported through the pipeline per unit time. For a given PCP with capsules running at a given speed, the throughput is directly proportional to the linefill – doubling the linefill will double the throughput and so forth. The conventional PCP systems used in Japan has limited throughput because the linefill is low – less than 3%. By using LIM instead of blowers, a tenfold increase in linefill is possible. A tenfold increase in linefill means the same pipeline system now can transport ten times more cargo, which will greatly reduce the cost for transporting each tonne of cargo through the pipeline.

Also, as the linefill increases, the air volume in the pipeline decreases. This means that less energy will be spent in moving the air in the pipe, and most of the energy will be spent in moving the cargo-carrying capsules. It makes the system more energy efficient. Another important advantage of using LIM for PCP is that the LIM pump is non-intrusive. It can be placed not only at the pipeline inlet, but also anywhere along the pipe. For long-distance PCPs, LIMs can be placed at intermediate stations along the long pipe or conduit, in the same way booster pumps work in ordinary long-distance oil and natural gas pipelines. This greatly facilitates the use of PCP for long-distance transportation of cargoes.

3. Advantage of Using Steel Wheels and Rail

In any type of wheeled vehicles, there are two sources of drag force – the aerodynamic drag which increases with the speed of the vehicle, and the contact friction which at ordinary operational speed is independent of speed but proportional to the rolling friction coefficient of the wheels. The smaller the rolling friction coefficient, the smaller the contact friction becomes, and hence the more energy efficient the vehicle becomes. The rolling friction coefficient of rubber-tired vehicles such as trucks is of the order of 0.01 (i.e., 1%). In contrast, for steel wheels rolling on steel rails, the coefficient is of the order of 0.002 or 0.2%, which is approximately five times smaller than that of trucks. Consequently, by using steel wheels instead of rubber tires for capsules, much energy can be saved, especially for vehicles that travel at low speed. For any PCP system that operates at high linefill or high throughput, most of the energy is spent in overcoming the contact friction rather than the aerodynamic resistance. The capsule speed used in the design of this project, approximately 15 m/s, is regarded as low speed. At such speeds, much energy can be saved by using capsules fitted with steel wheels rolling on steel rails. This shows a main advantage of using capsules with steel wheels rolling on rails. Another advantage of using rails is to offer good control of vehicles (capsules), in terms of the path of the vehicle and the ability to control the vehicle automatically, as for instance using standard rail switches for switching capsules to branches.

4. Project Description

The purpose of this DOE-sponsored project is to design and analyze an advanced PCP-system for transporting large quantities of minerals and/or mine wastes. The system designed is of 1m x 1m rectangular cross-section. It uses LIM to drive the system, and uses capsules that have steel wheels running on steel rails. As will be shown later, such a system with capsules running at 20 m/s can transport up to 50 million tones of minerals per year, having enough capacity for the largest mines in the world. Smaller-diameter systems for throughputs less than 5 MTY (million tonnes per year) are not investigated here, for they can better be served by conventional PCP systems using blowers, with capsules running inside a circular pipe of 1m diameter or less without rail in the pipe. The 1m x 1m size conduit used in this design has another advantage. It is sufficiently large so that a worker can walk or crawl inside the conduit to inspect its interior whenever a need arises. The PCP system studied in this project, with LIM and rails, combines the advantages of LIM with the advantages of rails, making it a super-performing and revolutionary advanced transportation system. The system is especially suitable for transporting cargoes that do not require high speed (not more than about 20 m/s), and when the throughput is high (at least 5 MTY).

Details about this study can be found in the Final Report of the project [8], which can be viewed and downloaded from the a website [9].

5. System Design

5.1. The Conduit

The conduit for this special PCP system has a cross-sectional dimensions of 1m x 1m, with rails on the bottom of the conduit. It can be made either of steel frame (see Fig.2) for above-ground construction, or concrete (see Fig.3) for underground construction. The cross-sectional geometry is shown in Fig.4.

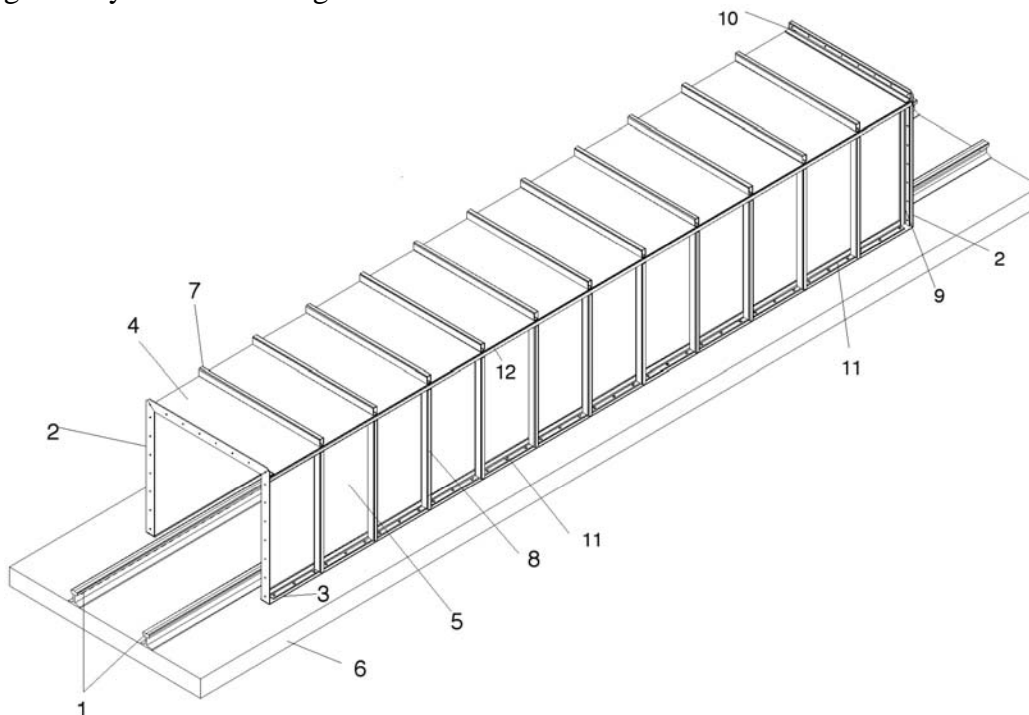


Figure 2. Rail-in-tube conduit made of steel frame and concrete floor for above-ground PCP



Figure 3. Rail-in-tube conduit with concrete wall and floor for underground PCP

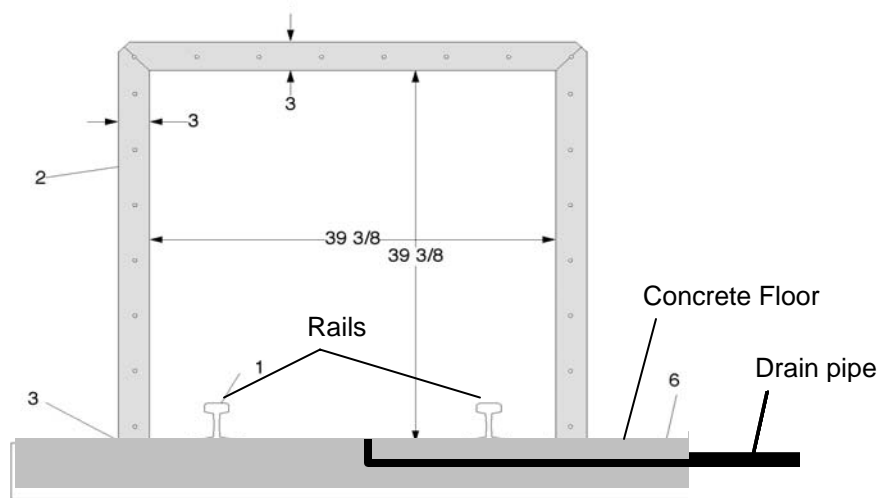


Figure 4. Cross-section of rail-in-conduit PCP

5.2 The rail

The rails used for this PCP standard ASCE 60-lb rail of 24-inch gauge. This means the spacing between the rails is 24 inches or 610 mm.

5.3 The Capsule

The capsule design is similar to that of a railroad car except for some modifications to suit the special need of this system, such as a bottom gate to discharge the cargo (minerals or mine wastes) by gravity, gadgets to activate the brake automatically, and a double-layer wall (steel inside and aluminum outside) to enable the capsule to receive the thrust of the LIM (linear induction motor) in an efficient manner. A drawing of the capsule is shown in Fig.5. The design of the capsule wall is shown in Fig.6, which shows a two-layer wall – a thin (2 mm) outer layer

made of aluminum, and a thick (10 mm) inner layer made of steel or cast iron. The two layers are required by the LIM to generate maximum thrust.

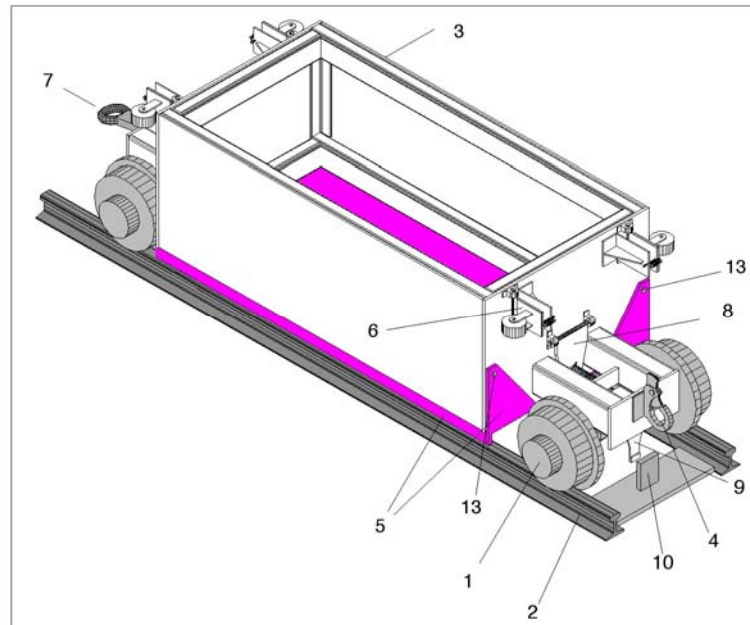


Figure 5 Capsule design

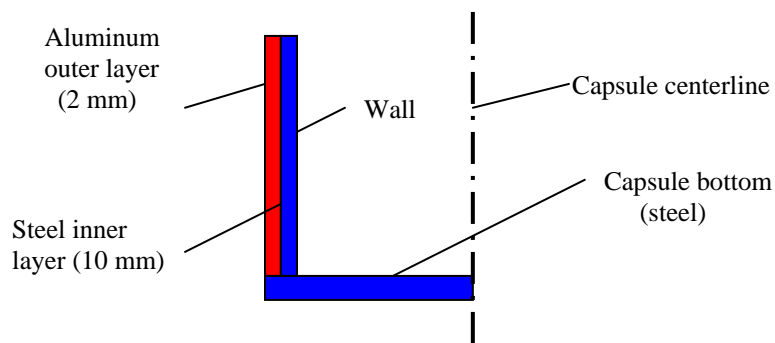


Figure 6 Capsule side walls (2-layer wall for use with LIM)

6. System Analysis

The special PCP system was analyzed by first deriving the hydrodynamic equations governing the motion of the air and capsules in the conduit, and the electromagnetic equations that govern the interaction between the stator (LIM) and the rotor (capsules) passing through the LIM. By solving these two sets of equations simultaneously, the behavior of the capsules through the LIM can be analyzed. The aerodynamic equations are different for the unsteady case as it is for the steady case. Both were derived separately so that they can be used to analyze both the steady state operation and the unsteady state or transient operation of the PCP.

The aforementioned equations and approach were used to analyze different cases of LIM-PCP, to see how the key system parameters, such as the LIM-pump efficiency, E_p , the capsule speed going through the LIM, V_c , and the thrust generated by the LIM, F_L , vary with throughput, T , and the relative length of the LIM, L'/L , where L' is the LIM length, and L is the pipe length. Examples of analytical results are given in Figs. 7-9.

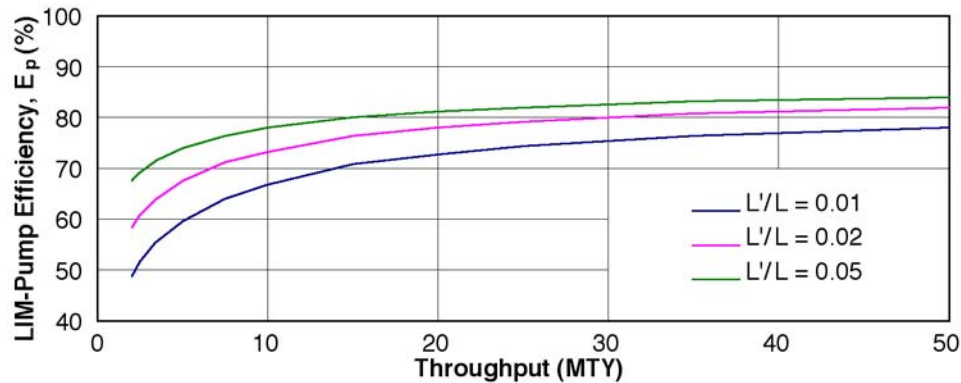


Figure 7. Variation of maximum LIM-pump efficiency with throughput and L'/L for $L=10,000$ m (delivery line).

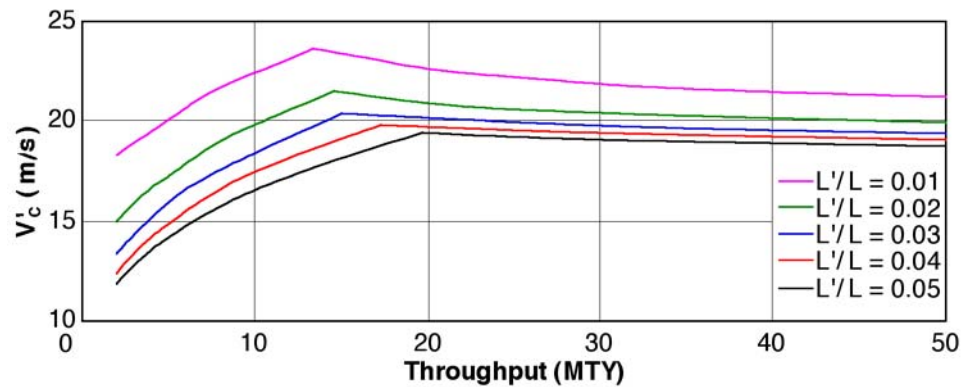


Figure 8. Variation of capsule velocity in LIM with throughput and L'/L (delivery line).

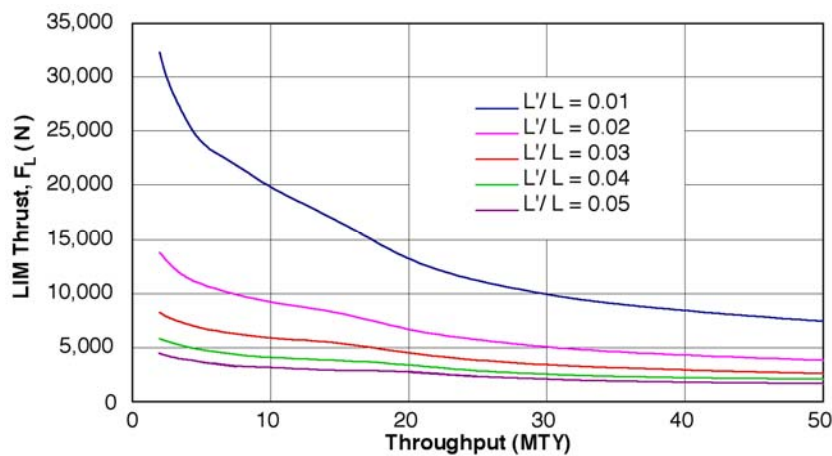


Figure 9. Variation of LIM thrust on each side of capsule as a function of throughput and L'/L (delivery line).

7. Cost Analysis

Using a life-cycle cost analysis that takes into account of many factors including the capital cost, annual operation and maintenance cost, taxes, depreciation, and a 15% of return-on-investment, the unit costs for transporting each tonne of cargo through the PCP of different lengths and throughputs were computed, and the results were given in Fig.10. It can be seen from the figure that the unit cost increases almost linearly with distance except for short distances – less than about 50 km, and it decreases rapidly as the throughput becomes large. For instance, for transportation distance of 100 km, the unit cost for the PCP running at throughput of 5 MTY is as high as \$32 (U.S. dollars). However, when the system is running at throughput of 50 MTY, the unit cost drops to about \$5 only. It is clear from this analysis that this advanced PCP system equipped with LIMs and rails is economical only for very large throughput, such as needed at very large coal mines, or when transporting the solid waste of a large city. Note that the foregoing analysis is based on a PCP that has two parallel lines: a delivery line for delivering the cargo, and a return line for returning empty capsules. For small throughputs, savings can be achieved by using a single line for both delivering loaded cargoes and returning empty cargoes. For relatively short lines, this can be done by running the pipeline in one direction as the delivery line during part of each day, and then running the pipeline in the opposite direction to return empty capsules during another part of each day. For long pipelines, the same can be accomplished by lengthening the cycle time of operation, such as three days in each direction.

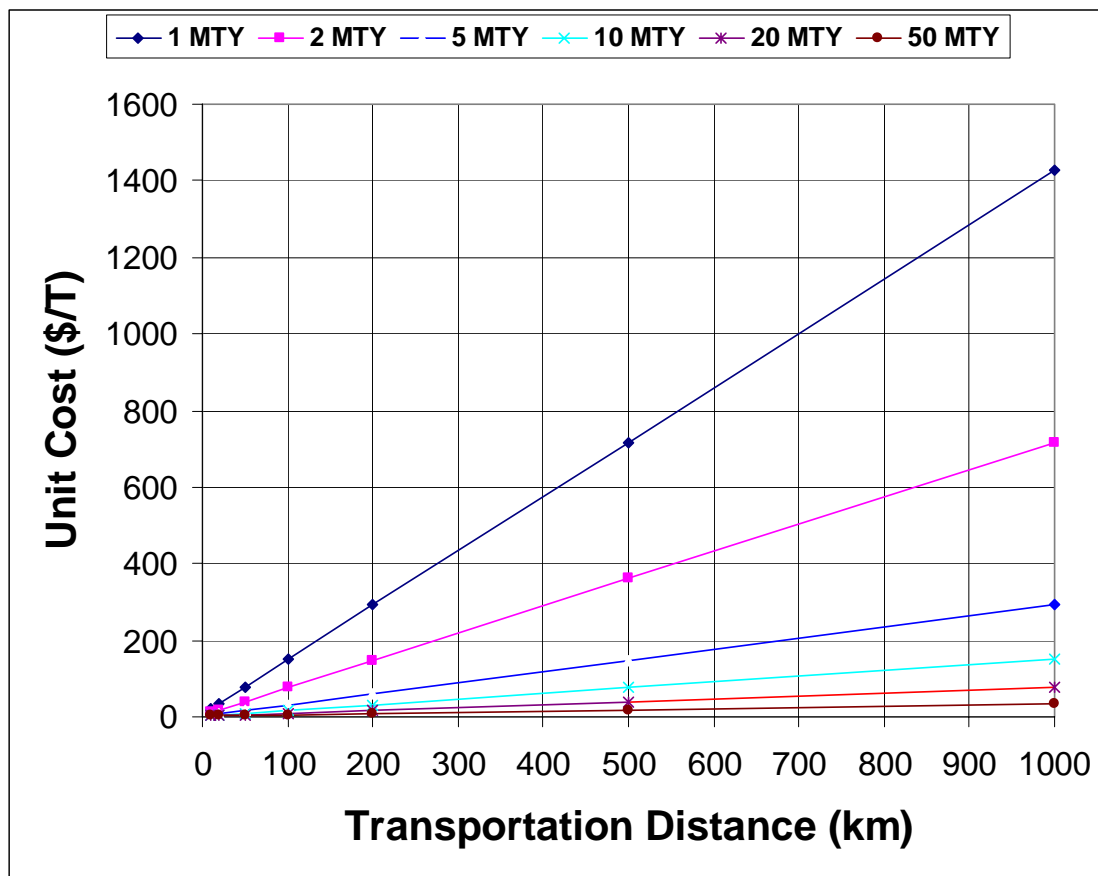


Figure 10. Variation of unit cost with transportation distance and throughput.

8. Energy Efficiency

The energy efficiency of any freight transportation system can best be determined from a quantity called the “*energy intensiveness*” or “*EI*”, which is defined as the energy needed to transport one unit weight of cargo over a unit distance. The units of EI used in the United States is Btu/TM, which stands for the BTU (British Thermal Unit) of energy used for transporting one ton (American ton, which is 2,000 lbs) of cargo over one mile of transportation distance. The average values of EI for oil pipelines, waterway (barge), railroads, trucks and airplanes are respectively 450, 550, 680, 2300 and 37000 Btu/TM [10]. It is of interest to calculate the EI of the LIM-driven PCP system studied in this report, and then compare the results with the above figures given for the other five modes to see how energy efficient is the LIM-driven PCP as compared to these other transportation modes.

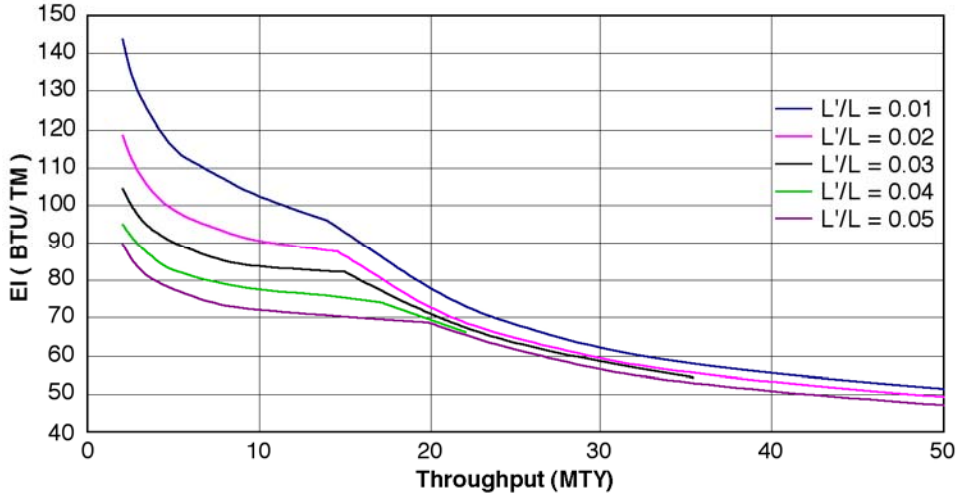


Figure 11. Variation of EI of LIM-driven PCP (delivery line)

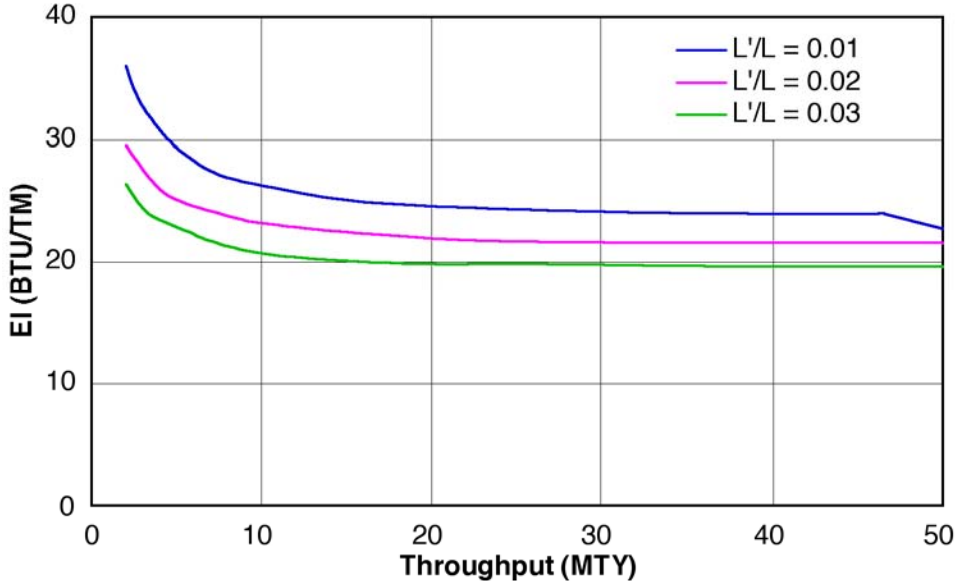


Figure 12. Variation of EI of LIM-driven PCP (return line)

Figure 11 shows that the EI of the delivery line decreases with increasing throughput, and decreases with increasing L'/L. This means both larger throughput and longer LIM make the system more energy efficient. However, even for the smallest throughput (2 MTY) and the shortest LIM (L'/L = 0.01) analyzed, the value of EI is 144 Btu/TM. If we divide this value by the corresponding LIM motor efficiency of 90 % obtained from the same study [8], the EI for the delivery line is still only 160 Btu/TM. For the return line at 2 MTY and L'/L = 0.01, Fig.12 yields an EI value of 36 Btu/TM, and the corresponding LIM motor efficiency is known to be 76 %. This means the actual EI for the return line is 47 Btu/TM. Adding the two EI values (one for the delivery line and the other for the return line) yields the total EI of the system, which is 207 Btu/TM. Comparing this value with the value of 680 Btu/TM for ordinary railroad and 2300 Btu/TM for truck, it can be seen that the LIM-driven PCP technology for this small throughput of 2 MTY uses approximately 30 % of the energy used by railroad train and uses approximately 9 % of the energy used by truck to transport the same cargo over the same distance.

If we increase the throughput to 50 MTY, the value of using PCP is even more impressive. For the delivery line, Fig. 11 yields an EI value of 52 Btu/TM. With a corresponding motor efficiency of 89 %, the actual EI value for the delivery line is 58 Btu/TM. For the return line at 50 MTY and L'/L = 0.01, Fig.12 yields an EI of 24 Btu/TM. With a motor efficiency of 85 %, the actual EI for the return line is 28 Btu/TM. Adding the EI of the delivery line to the EI of the return line yields the total EI of the system, which is 86 Btu/TM. This value is only 13% of the energy used by ordinary railroad and 4% of the energy used by truck, for transporting the same cargo over the same distance. This shows the great value that the LIM-driven PCP can have in conserving energy, especially for systems that require large throughputs, and when the PCP is used in lieu of truck instead of train (railroad). Even when using this PCP in lieu of railroad, much energy can be saved if the throughput is high.

9. Conclusion

1) The advanced PCP system driven by LIM and using capsules running on steel rails is highly energy efficient – The system has an EI (energy intensiveness) between 50 Btu/TM (for the largest throughput of 50 MTY) and 140 Btu/TM (for the smallest throughput of 1 MTY). In contrast, the average EI of truck is 2,300 Btu/TM, and of train is 680 Btu/TM. This means that even at the lowest throughput of 1 MTY, the advanced PCP system studied uses less than one-tenth of the energy used by an average truck and less than one-fourth of the energy used by an average train, for transporting the same amount of cargo over the same distance.

2) The system is environmentally friendly -- By using such underground PCPs instead of aboveground trucks and trains for transporting minerals or solid wastes, traffic jam, accidents and noise causes by trucks on roads and by trains at rail crossings are eliminated. Since the PCP system is powered electrically, air pollution (emission of diesel fume) generated by trucks and trains are also eliminated.

3) The system has a huge throughput range between 2 MTY and 50 MTY -- Within this range the system can run smoothly not only continuously but also intermittently including startup, shutdown, and restart. For any throughput less than 2 MTY, the system is not only uneconomical but also may have problems running smoothly. It is possible to run the system for throughputs higher than 50 MTY, but the logistic for feeding capsules into the tube and for loading capsules with minerals or wastes becomes very challenging.

4) High efficiency -- It is possible to design highly efficient LIM pumps for this system with motor efficiency approaching 90% at capsules speed of 15 m/s approximately. Higher efficiency can be obtained when capsule speed is higher.

5) Cost Effectiveness -- For very large throughput, such as above 10 MTY, this PCP system can be cost-effective as compared to using trucks by using twin tubes (double conduits) – one for the delivery line to transport loaded capsules and one for the return line to return empty capsules. However, for throughputs less than about 10 MTY, to make the system cost-effective will require the use of a single tube or conduit, used alternatively for delivery of loaded capsules and for the return of empty capsules. To reduce cost for such relatively small throughputs, further consideration should be given to operating the system periodically, such as running the single-tube system at high capacity during day time and stopping the system at night, and so forth. For throughput less than 5 MTY, the conventional PCP using steel pipe without rail in the pipe, and using blowers instead of LIM will be more economical, except for long-distance operation that requires booster pumps.

6) Safety and security -- Because the PCP system is enclosed and the capsules cannot run outside the fixed route of the conduit, the system is much safer than other surface transportation modes. Also, the system is most secure because capsules cannot be hijacked by terrorists and used as truck bombs to attack another target. Also, being underground, it is far more difficult to sabotage a PCP than to sabotage a truck or train. The damage that can be inflicted on an underground PCP by sabotage is rather limited, and it can be quickly repaired using current emergency-response practice and equipment developed and used for emergency repair of oil and natural gas pipelines. Therefore, one can conclude that using the PCP instead of truck or train to transport minerals and mine wastes enhances transportation security.

10. Acknowledgment

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