Preliminary Design of the Magplane MagPipe System

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ABSTRACT: A novel capsule pipeline transportation system using a linear synchronous motor, called Magplane MagPipe, is under development with the intention to replace trucks and railways for hauling materials from the mine to the rail head, power plant or processing plant with reduced operating cost and energy consumption. The initial demonstration of a MagPipe line in Inner Mongolia will be a 500 meter long double-pipe coal transport system with the design transportation capacity of 3 Mega-tonnes per year. The pipeline consists of 6 meter long plastic pipe modules with an I-beam suspension system inside the pipe to carry sets of five coupled capsules. The pipe will also contain non-continuous motor winding modules spaced at 50 meter intervals. A set of Halbach-arrayed permanent magnets on the bottom of the capsules interact with the linear motor windings to provide propulsion. The motor is driven by variable frequency drives outside the pipe to control the speed. This paper describes the preliminary design results of MagPipe system.

1 INTRODUCTION

A novel capsule pipeline transportation system using a linear synchronous motor, called MagPipe, developed by Magplane Technology, Inc. can be used to transport any mined materials normally transported in trucks. Globally, coal is the third most heavily mined material after sand and gravel. According to a report from the World Coal Institute (www.worldcoal.org), up to 70% of the cost of coal is transportation costs [1] and, considering global coal production of 5,300 million tonnes, Magplane estimates that the use of short-haul diesel trucks to transport coal from mines to local transportation centers costs at least $8 billion worldwide each year. Transportation of coal by truck uses large quantities of diesel fuel, which is energy inefficient, costly and a source of local pollution. Significant maintenance is also required for the trucks and for the road infrastructure. Transportation of coal by rail requires circuitous routes in hilly terrain and limitations on mining within 500 meters of the rail right-of-way often block access to significant reserves of coal. Transportation of coal by coal-water slurry pipelines generally carry severe environmental pollution in pumping ground water at the origin and disposing of slurry water at the terminus. Other potential forms of capsule pipelines, such as pneumatic pipelines have high energy requirements and limit throughput relative to the linear motor drive pipeline, because the conventional pneumatic systems use external blowers to move the column of air together with the capsules in the pipe.

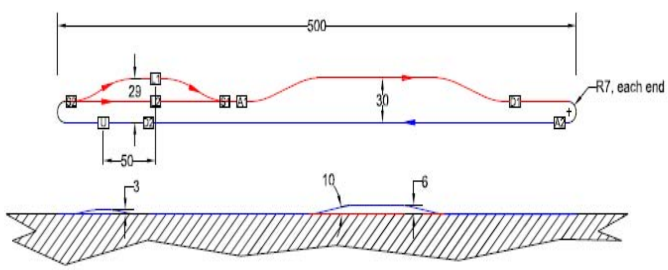
A prototype pipeline system using a linear synchronous motor drive was constructed and demonstrated in 2001 at the IMC-Agrico Company in Lakeland, Florida [2-3]. The prototype demonstration line used a 270 meter of 60 cm diameter cylindrical fiberglass tube, and included a 60 meter long accelerator/decelerator section, a switch, and load and unload stations. The test vehicle traversed back and forth at speeds up to 18 m/s. The 2.4 meter long wheelbase vehicle used six-wheel assemblies at each end of a rotating hopper, and had a payload capacity of 270 kg. The vehicle carried an array of neodymium-iron-boron permanent magnets with back iron which interact with the linear motor mounted on the outside of the tube to provide propulsion, and with external coils to provide an electromagnetic switch function.

Based on the Florida prototype pipeline system, we have made a series of innovations on the MagPipe pipeline transportation system. The most significant technical innovation is to replace the on-board North-

South magnet array and the backiron with Halbach-arrayed permanent magnets and also to put non-continuous linear motor windings inside the pipe to decrease the gap between propulsion magnets and linear motor windings by half. The two changes together increased the motor propulsion force per Ampere by several times.

China and the United States are the two largest coal producers in the world with combined annual production of more than 60% of the global coal production. The initial MagPipe Baotou demonstration line in Inner Mongolia is a 500 meter long double-pipe coal transport system with a design transportation capacity of 3 Mega-tonnes per year. This paper presents the preliminary MagPipe design results as well as an economic analysis.

2 BAOTOU DEMONSTRATION PROJECT



L1, L2 Load stations
U Unload station
A1, A2 Acceleration sections
D1, D2 Deceleration sections
S1, S2 Switches

Figure 1. Layout of the Baotou Demonstration Line.

The layout of Baotou demonstration project is shown in Figure 1. The Baotou Demonstration Line is a two pipe system with a 500 meter outbound leg and a 500 meter return leg. Both load and unload stations are at the same end of the line, facilitating transfer of the unload pile back into the load silo. The far end of the line will contain a 180 degree U-turn to reverse direction of travel and transfer the capsule set from the outbound to the return line. There will also be a U-turn at the load/unload end of the line to reverse direction after unloading and before moving into one of two parallel load stations. The capsule design speed is 10 m/s, but the capsule sets will be driven by mechanical means in the U-turns and the load/unload regions at a low speed of 2 m/s.

The demo line will be built as a combination of straight lengths and horizontal and vertical curves with an artificial hill to demonstrate full grade-climbing capability. The curves in the 10 m/s portion of the line will have minimum bend radii of 70 meters. There will be an artificial steel-bridge hill in the return pipe with 10 degree climb and decline slopes each with 40 meters in length, and a 50 meter length on the flat top. The artificial hill bridge structure will be 6 meters high. The unload end of the return pipe will also be elevated at the unload station by 3 meters to allow space under the pipe for accumulation of the unloaded coal.

The end of the outbound line will be connected into a workshop shed with a control room to allow repair and inspection of capsule sets. The indoor portion of the line can also be used as a low speed section to test integration of the local and global controls prior to completion of the full project.

The Baotou Demonstration Project has the objectives of demonstrating all system operations necessary for a commercial system, including a re-start after an un-planned shut-down following a power failure, the management of all fault conditions identified in commercial operation by simulated faults on the demonstration, and demo system operating cost projection to a commercial system, such as energy consumption, scheduled maintenance, and necessary operating personnel with a satisfactory return on investment and successful market penetration against both truck and rail transport.

After the initial 500 meter long double-pipe demonstration line in Inner Mongolia, the first commercial demonstration line will be a 2 km long double-pipe system with a capacity of 3 Mega-tonnes/year and will be followed by a 10 km extension at 6 Mega-tonnes/year.

3 PRELIMINARY PIPELINE DESIGN

3.1 System Overview

The MagPipe pipeline is composed of 6 meter long plastic pipe modules with an outbound and a return pipe. As shown in Figure 2, a 110 cm inner diameter plastic pipe encloses an I-Beam suspension system which carries sets of five coupled capsules. The pipe also contains non-continuous linear synchronous motor winding modules spaced at 50 meter intervals. A set of Halbach-arrayed permanent magnets on the bottom of the capsules interact with the linear motor windings to provide propulsion. The motor is driven by variable frequency drives outside the pipe to control the speed.

Load and unload stations will accommodate the five capsule sets, loading or unloading five capsules simultaneously. The five-capsule sets will be launched every 10 seconds and travel at 10 m/s in the pipe. A velocity of 10 m/s corresponds to a frequency of 42 Hz from the linear motor drive.

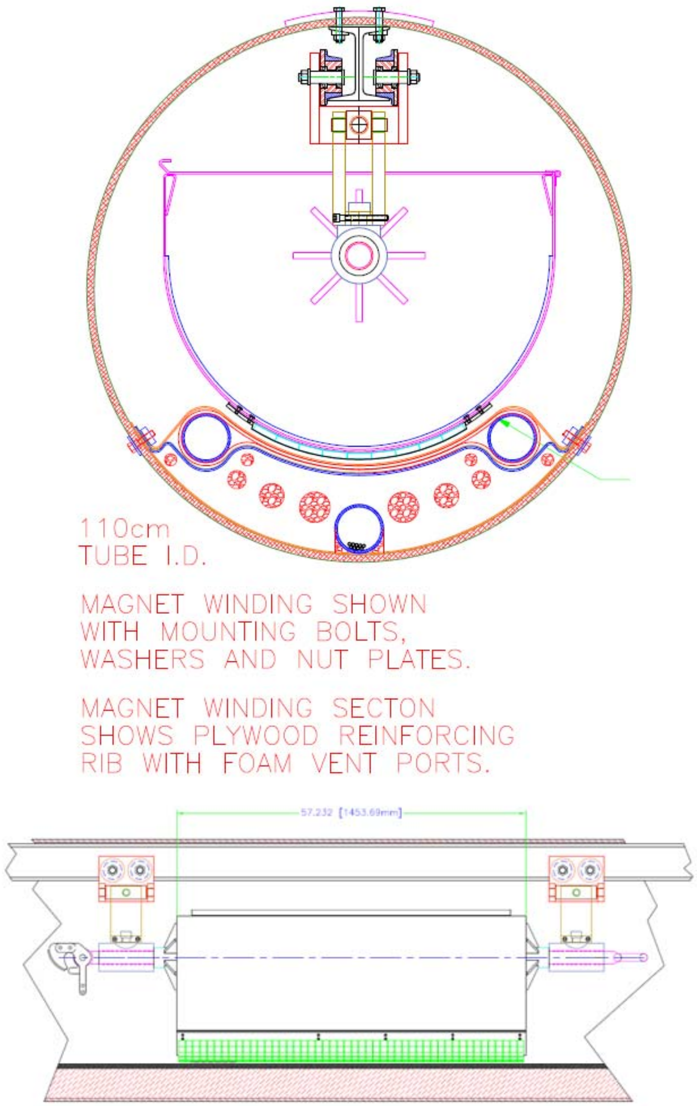


Figure 2. Overview of pipe module, I-beam suspension, motor winding, and capsule pipe.

Table 1. Parameters of permanent magnets

Magnet grade	N40 (NdFeB)
Basic magnet block	0.03×0.0125×0.05 m
Block number for one Halbach array	72
Block number for one capsule	432
Halbach array wavelength	0.24 m

Some parameters of permanent magnets are listed in Table 1. The basic magnet block size is 3 cm long, 1.25 cm high, and 5cm wide. Eight basic magnet blocks form a 0.24m long Halbach array with the magnetization rotated 45 degrees from the previous magnet. Nine blocks of magnet are put in parallel, making one Halbach array 0.24 meter long, 1.25 cm high, and 0.45 meter wide. There are 6 wavelengths of Halbach arrays on the bottom of each capsule, and each capsule has 432 blocks of magnets on the bottom. Table 2 summarizes some parameters of the motor winding. The working gap between the permanent magnet arrays and the linear motor windings is 15 mm. The typical capsule parameters are listed in Table 3. Depending on the packing density of the coal, the capacity of the capsule ranges from 240 kg to 480 kg, which is correspondent with the annual transportation capacity of 3~6 Mega-tonnes/year.

Table 2. Motor winding parameters

Cable	Copper AWG#6
Wavelength	0.24 m
Pitch	0.12 m
Motor width	0.6 m
Cable layer thickness	0.01 m
Gap between magnets and LSM windings	0.015 m

Table 3. Typical capsule parameters and annual transportation capacity

Empty weight	388 kg
Payload	347 kg
Weight of a 5-capsule train	3675 kg
Annual transportation capacity	4.6 Mega-tonnes/year

3.2 Pipe

The pipe module is 6 meters in length. For flat ground installation, two 6-meter pipes will be coupled together in the factory and have a 12 meter I-beam installed. Pipe sections carrying a motor winding will also have the motor winding factory installed. The pipe diameter can be varied depending on the desired capacity of the pipeline. A pipeline system with the capacity of 3 Mega-tonnes per year requires a 110 cm inner diameter plastic pipe with a 1.5 cm wall.

Vertical curves in the system will be made by 5 degree off-sets between straight pipe sections, accommodated by one meter long flexible connectors between pipe sections. Horizontal curves will be made of 6 meter long flexible polyethylene drainage pipe containing a six meter arc of rolled I-Beam with a minimum of 70 meter radius. Long curves will contain straight sections every 50 meters to accommodate motor modules.

3.3 *I-Beam and Capsule Suspension*

Capsules are suspended from front and rear sets of wheels that ride on an I-beam section attached to the inside top surface of the pipe in a monorail suspension. The I-beam is made from two back-to-back standard carbon-steel C-channels. Use of this innovative monorail beam suspension allows accurate alignment at the ends of each module to be preset by tooling jigs and locked in place so that a close tolerance module-to-module joint will be achieved when the modules are joined in the local site. This alignment of I-beam sections provides a continuous and smooth surface between modules in order to improve the effective friction coefficient and avoid the periodic pipeline disturbances found in the Florida prototype system due to the pipeline connection surface discrepancies between two pipe modules.

In the improved version, each capsule has eight 10 cm diameter wheels in contact with the I-Beam. One set of four wheels precedes and one set follows each capsule. A vertical curve connector fabricated from rolled C-channel on a 10.7 meter radius is shown in Figure 3. Horizontal curves use 6 meter long rolled C-channel with a 70 meter turn radius and have a continuous flexible pipe enclosure.

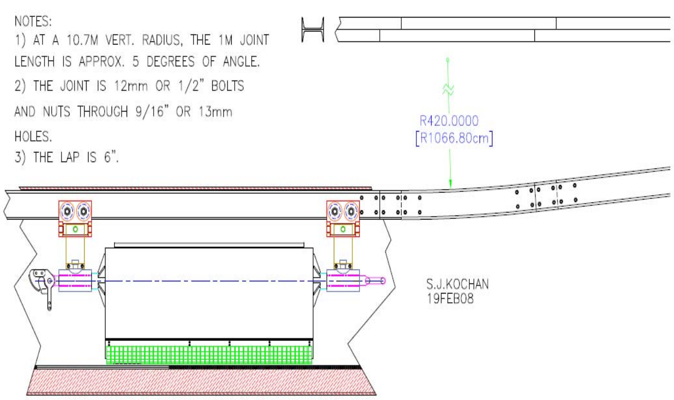


Figure 3. A vertical curve of I-beam suspension.

3.4 *Capsule*

The improved capsules have tight fitting covers that prevent the loss of the capsule content when traveling through the pipe. This is particularly important in carrying coal where coal dust consists of fine powder, and accumulation in the pipe can represent a hazard. The cover is swung open during loading and unloading and closed prior to entering the pipe. The capacity of the capsule ranges from 240 kg to 480 kg with the typical value of 347kg depending on the packing density of the coal. The empty capsule and suspension weighs 388kg. There are 100 individual capsules per route km of double pipeline.

3.5 *Linear Synchronous Motor Windings*

The motor windings are mounted inside the pipe and can be easily replaced by removing a module in the event of accident. Module joints are designed so that an entire module can be replaced when necessary for repair. As shown in Figure 4, each phase of the 3-phase winding is wound from a single cable length wound in five passes with turns around at the end of the module and therefore all five turns are in series. The windings are not continuous along the pipeline, and typically are inserted one pair in every 50 meters. This approach reduces the motor cost significantly.

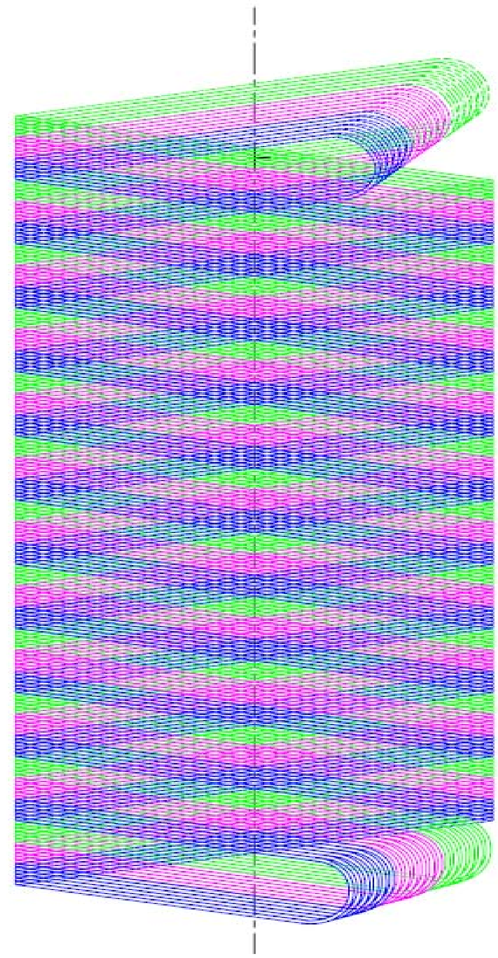


Figure 4. Plan view of three phase linear synchronous motor.

On flat ground there are two adjacent 6 meter-long motors every 50 meters. Therefore there will be forty motor winding modules for ever km of double pipe. On 5 degree slopes there are four 6 meter-long motors every 50 meters. A double pipe on a sustained

5 degree slope would have 160 motors per km. On 10 degree slopes there are continuous motors, that is eight 6 meter-long motors in every 50 meters. A double pipe on a sustained 10 degree slope would have 320 motors per km. The acceleration and deceleration sections each have six 6 meter-long motor modules, a total of 24 motors per system.

3.6 Magnet Array

As shown in Figure 5, one wavelength of Halbach array has eight blocks of magnets with rotated magnetization degrees. The magnet array of each capsule consists of six wavelengths of eight rows of Halbach-arrayed blocks, and each row is composed of nine blocks of 50 mm long, 30.0 mm wide and 12.5 mm thick magnets. There are 56 kg of magnets in each 6-wavelength capsule array (25% at 0 degree magnetization angle, 25% at 90 degree angle and 50% at 45 degree angle). For 100 capsules per route km, 5.6 tonnes of neodymium-iron-boron grade N40 magnets are required.

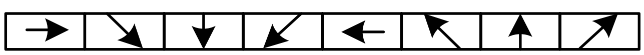


Figure 5. One wavelength of Halbach-array permanent magnets

During assembly contact cement is used to hold the blocks in place. When mounted on the hopper the magnet array is covered with a stainless steel sheet which secures the blocks in place and protects the surface.

3.7 Multi-car Metered Loading Mechanism

The improved loading station has the option to provide two or more parallel loading positions. For example, if it is necessary to launch a capsule set every 10 seconds to provide the required hourly capacity, but takes 20 seconds to load, two stations can be used and alternately launched into the pipe. In the improved loading station an innovative mechanism is employed that can load five cars simultaneously with a metered volume of coal. As shown in Figure 6, a cylinder containing 5 pockets will rotate under a storage silo, first exposing the five pockets to the storage volume and then rotating by 180 degrees to empty the pockets into five chutes positioned above the five capsules.

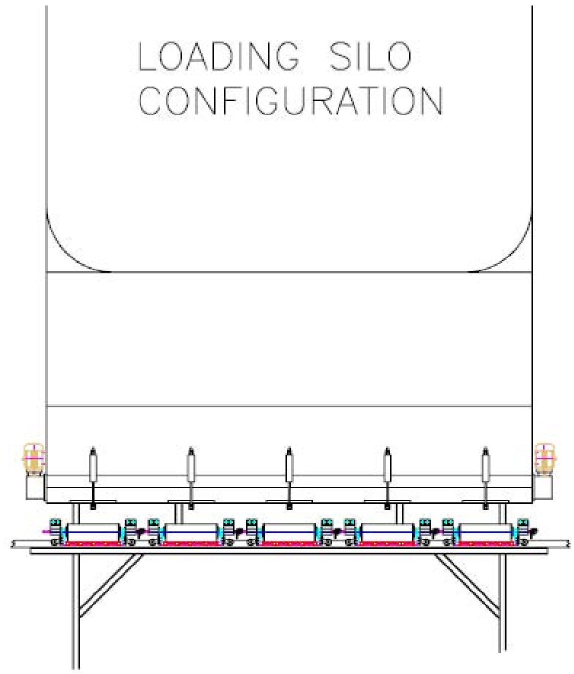


Figure 6. Multi-car metered loading mechanism.

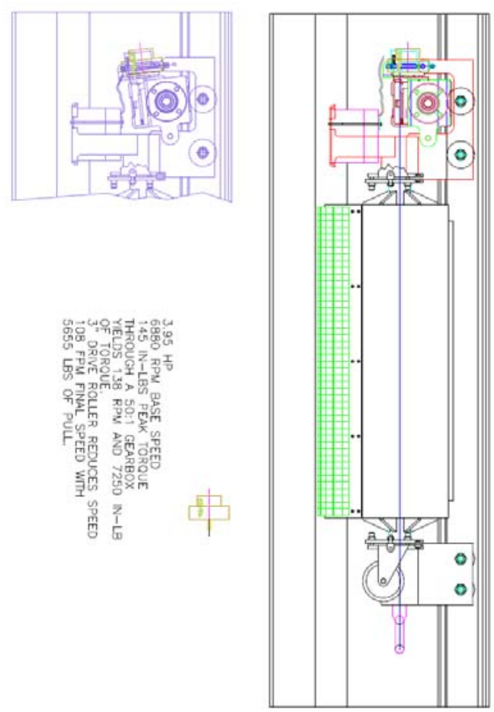


Figure 7. Rescue “tug” mechanism.

3.8 Power Failure Recovery System

The improved pipeline transport system will have multiple layers of protection against utility power failures. The first level of defense will use stored energy devices on the utility side to “ride out” short-term power outages, typically less than 10 seconds.

These stored energy devices will also supply control power during a controlled shutdown of the system during longer duration power outages. In the second level, capsule sets will coast under their own momentum and will be automatically brought to a stop over a motor winding. In the unlikely event that some local system failure results in one or more capsule sets not being captured over a motor winding, an operator controlled “rescue” mode as shown in Figure 7 will be utilized to move the capsule set to the nearest motor. Each five-capsule set will carry an innovative small motorized “rescue pod”, which travels on the I-Beam and contains a compact battery operated gear motor that can tow the set at low speed for a limited distance. Communication with the rescue pods will use a wireless network.

3.9 Global Control System

As shown in Figure 8, the functions of the global control system include tracking the capsule sets using sensors by radio frequency tags, instructing the local control blocks, starting up the system from a stopped condition, shutting the system down in a controlled manner, collecting configuration and operation data for analysis, and dealing with system faults in a safe manner. Local system control capsule speeds within the blocks are based on instructions from the global system control. The global control system also regulates acceleration and deceleration and sends instructions to the loading, unloading and maintenance bypass operations.

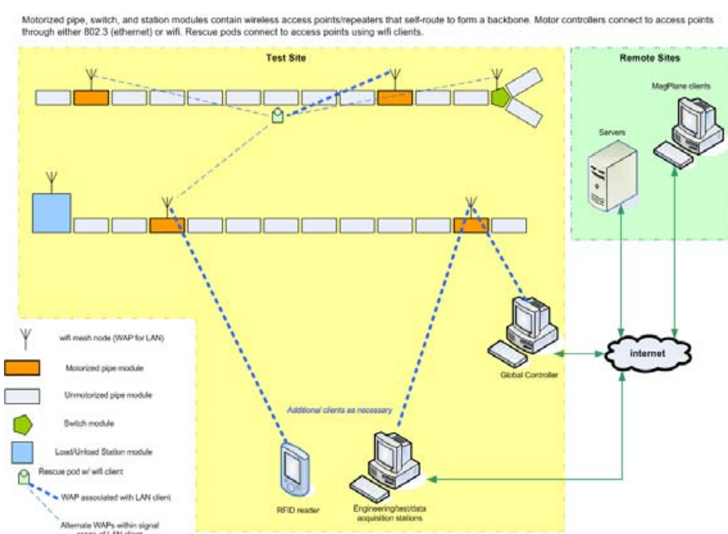


Figure 8. Scheme of the global control system.

4 ECONOMIC ANALYSIS

The cost of MagPipe pipeline transportation systems will be project specific and will depend on capacity, length, terrain, uphill grades on outbound (loaded) direction, and custom features that may be required. Two coal transportation routes with large and small capacities in Inner Mongolia have been analyzed as follows to assess the economic advantage of MagPipe coal transportation over truck transportation.

Large capacity application:

Production of 35 Mega-tonnes per year transported 40 km between collection and distribution hubs.

Trucking costs

- Using 35-tonne dump trucks, 1 million truck dumps per year are required
- 31.7 million litres of diesel fuel consumed causing severe pollution
- Annual trucking costs @ US$0.08/t-km = US$112M

MagPipe costs to the client

- A 35 Mt/year MagPipe can be designed using larger physical size and higher load factors
- Estimated cost to build = US$220M (two pipelines for round trip)
- Annual operating costs @US$0.011/t-km = US$15M (savings of $97M / year)

The total net cost reduction over 10 years is US$742M.

Small capacity application:

A typical mine to rail head transportation route was selected for analysis:

- 20 km truck route between mine and rail head
- 15 km MagPipe direct route between mine and rail head
- Coal production of 3 Mt/year

Trucking costs

- Total costs are between 8 to 11 cents USD per tonne-km
- At the lower estimate of 8 cents per tonne-km trucking costs are US$4.8M / year
- Use of diesel fuel contributes to local pollution

MagPipe costs to the client

- MagPipe cost to build = US$32.1M (two pipelines for round trip)

- MagPipe operating costs at $0.026/t-km = $1.17M (savings of $3.63M / year)

The net cost reduction over 10 years is US$3.7M.

According to our economic analysis, MagPipe transportation solutions are economically superior to diesel dump trucks for capacities above 2 Mt per year in China. The cost savings increase significantly with capacity and distance. Cost superiority is even greater in other countries such as the United States where truck operating costs are substantially higher than in China.

5 CONCLUSIONS

We have successfully completed the preliminary design of the innovative MagPipe transportation system. The initial demonstration of a MagPipe line in Inner Mongolia will be a 500 meter long double-pipe coal transport system with a design transportation capacity of 3 Mega-tonnes per year with a large potential to replace trucks and railways for hauling coal from the mine to rail head, power plant or processing plant at reduced operating cost and energy consumption. The economic analysis indicates that the MagPipe transportation system is economically superior to the diesel dump trucking system for annual capacity more than 2 Mega-tonnes in China and the cost savings increase significantly with capacity and distance.

6 ACKNOWLEDGEMENT

The authors wish to thank members of the MagPipe team for their help on this paper, in particular Stephen Kochan for design and Jason Mill for economic analysis.

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