A New Pipeline System Transporting Coal Ores

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ABSTRACT: A 70m-long prototype pipeline system using a linear synchronous motor is currently under demonstration in Baotou, China, with the purpose to replace trucks and railways for hauling coal from the mine to the rail head, power plant or processing plant at a reduced operating cost and power consumption. The new pipeline system with heavier coal-carrying capsules will replace the current I-type hanging rail system with two new C-channel rails located at two sides of pipe with U-type stanchion every 12m along the pipeline made with standard 12m-long non-metallic pipe modules. The new capsule with double the transport volume has large load wheels to accommodate the heavier payloads of coal ores and side wheels to guide the capsules to prevent the permanent magnet Halbach arrays attached on the bottom of capsules from ever touching the motor windings. The new pipeline transportation system needs much stronger motors to drive the large heavy capsule set. A longer 1km demonstration line will be built in Baotou as a pre-commercialization step with the design transportation capacity of 10 Mega-tons per year of coal ores. This paper describes the preliminary design of new pipeline system, including several motor improvements, safety issues, and restart strategy.

1 INTRODUCTION

A 70m-long race-track prototype pipeline system using a linear synchronous motor developed by Magplane Technology, Inc. is currently under demonstration in Baotou, China, with the purpose to replace trucks and railways for hauling coal from the mine to the rail head, power plant or processing plant at a reduced operating cost and reduced energy consumption [1-2]. As shown in Figure 1, the demonstration is inside a 100 m long, 40 m wide assembly building on the Baotou site. The capsules are suspended from an overhead steel I-beam. Each 110 cm diameter 12m-long pipe leg contains two 3m-long linear synchronous motors. One capsule is accelerated to 2 m/s in one leg, cruises through the 7 m radius curve and is re-accelerated by the other leg, and then cruises back to the first leg through the other 7 m radius curve to make a short oval roundtrip in 20 seconds.

The new pipeline system with heavier coal-carrying capsules presents a challenge for the motor design and pipeline structure. Based on the Baotou prototype pipeline system, we have made a series of innovations in the new pipeline system. The most significant technical innovation is to replace the previous I-type hanging rail system underneath the top of pipe with two new C-channel rails located at two sides of pipe with U-type stanchion each at every 12 m along the pipeline as shown in Figure 2, in order to assure adequate improvement on the rail stiffness. The pipeline consists of 12m-long standard non-metallic pipe modules and each pipe module contains either one or four 3m-long standard motor winding modules. The new coal-carrying capsule with double transport volume has large load wheels to accommodate the heavier payloads of coal ore and side wheels to guide the capsules to prevent the permanent magnet Halbach arrays attached on the bottom of capsules from ever touching the motor windings. The new pipeline transportation system needs much stronger motors to drive the large heavy capsule set. A 1km demonstration line will be built in Baotou as a pre-commercialization step with the design transportation capacity of 10 Mega-tons per year of coal ores. Upon completion of the 1 km test system in 2012, the first 12km-long commercial line will be constructed to carry coal ores in Erdos, Inner Mongolia. This paper will briefly describe the 1 km demonstration line and present the preliminary design results of new pipeline system.

Figure 1. A 70 meter long oval demonstration in Baotou, China.

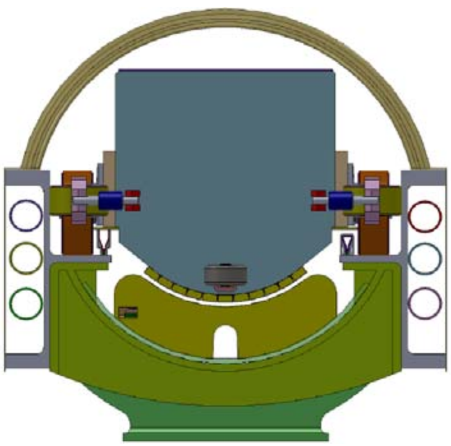

Figure 2. Cross-section of new suspension with two C-channel rails.

2 1 KM BAOTOU DEMONSTRATION LINE

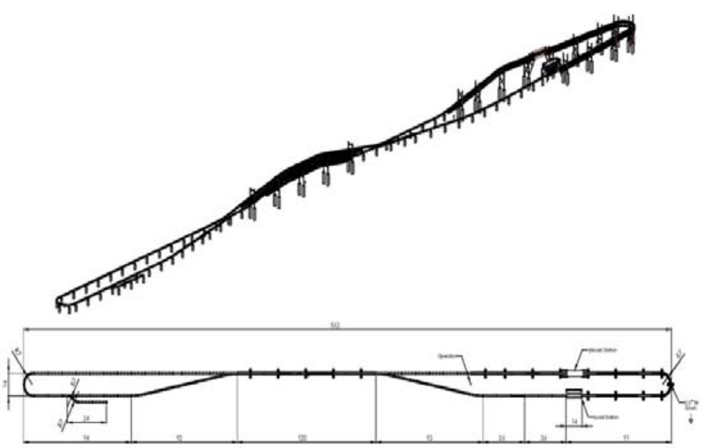

Figure 3. Layout of Baotou Demonstration Line.

The layout of the Baotou demonstration pipeline is shown in Figure 3. According to this pre-commercialization demonstration pipeline, the 1km long pipeline consists of an outbound and a return pipe with two 180 degree U-turns at two ends to reverse the travel direction, and one load station and one unload station will be set at the same end in order to return the unloaded materials back into the load station conveniently. Therefore, the 1 km long pipeline is divided into following four quadrants, outbound pipeline (Quadrant A), return pipeline (Quadrant B), unload station (Quadrant C), and load station (Quadrant D). Both load and unload stations can accommodate a five-capsule set, loading or unloading five capsules simultaneously.

The demonstration 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 capsule design speed is 10 m/s, but the capsule sets will be driven by the 2.5 degree down slope in the U-turns with the bend radius of 7 meters, and the load/unload regions at a lower speed around 3 m/s. The curves in the 10 m/s portion of the line will have a minimal bend radius of 70 meters. At the beginning, the fully loaded capsule set will exit the load station, start to accelerate to the operation speed of 10 m/s by the initial acceleration motor sections, pass the flat ground, 10 degree upslope, 10 degree down slope, and then go back to the return pipe through a U-turn. The capsule will also travel through a 10 degree slope hill and decelerate to be stopped over the unload station.

The Baotou Demonstration Line has the objectives of demonstrating all systems operations necessary for a commercial system, including the initial startup, a restart after an unplanned shutdown following a power failure and management of all fault conditions identified in commercial operation by simulated faults on the demonstration. It will also contribute to a determination of demo system operating cost projected to a commercial system, including power consumption, scheduled maintenance, and necessary operating personnel. The projected operating cost needs to have a satisfactory return on investment and successful market penetration against both truck and rail transport.

Figure 4 shows a standard 12m-long pipe module with a 5-capsule train. The pipe upper covers have been removed in the illustration for better visibility of the five capsule set. There are permanent magnets on the bottom of the capsules. Some parameters of permanent magnets are listed in Table 1. The basic magnet block size is 3 cm long, 2.5 cm high, and 5 cm wide. Eight basic magnet blocks form a 24 cm long Halbach array with the magnetization rotated 45 degrees from the previous magnet. Eleven blocks of magnet are put in parallel, making one Halbach array 24 cm long, 2.5 cm high, and 55 cm wide. There are totally 8 wavelengths of Halbach arrays on the bottom of each capsule, and each capsule has 704 blocks of magnets on the bottom. Table 1 also summarizes some parameters of the motor winding. The working gap between the permanent magnet arrays and the linear motor windings is 1.5 cm. The typical capsule parameters are listed in Table 2. Depending on the packing density of the coal, the capacity of the capsule ranges from 750 kg to 1,250 kg, which is correspondent with the annual transportation capacity of 7.5-12.5 Mega-ton/year.

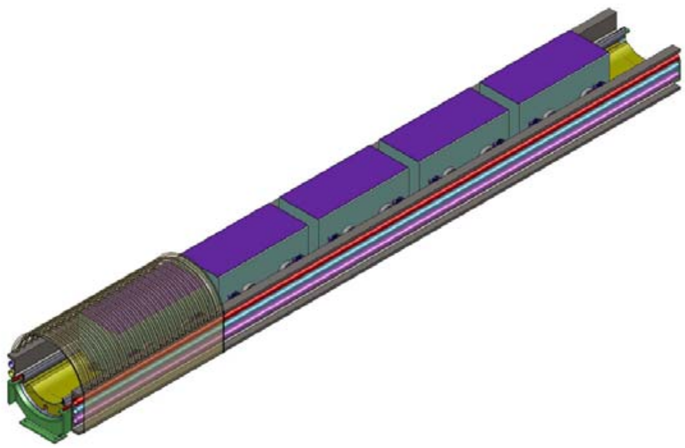

Figure 4. A standard 12m-long module with a 5-capsule train (removed pipe upper covers for better visibility of the five capsule set).

TABLE 1
PARAMETERS OF PERMANENT MAGNETS AND MOTOR WINDINGS

PERMANENT MAGNETS	
Magnet grade	N40 (NdFeB)
Basic magnet block	0.03×0.025×0.05 m
Block number for one Halbach wavelength	72
Block number for one capsule	704
Halbach array wavelength	0.24 m
MOTOR WINDINGS	
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 2
TYPICAL CAPSULE PARAMETERS AND ANNUAL TRANSPORTATION CAPACITY

Empty weight	974 kg
Payload	1,040 kg
Weight of a 5-capsule train	10,070 kg
Annual transportation capacity	10 Mega-ton/year

3 3 M MOTOR DESIGN FOR STANDARD 12M-LONG MOTOR MODULES

The new 1km-long demonstration pipeline transportation system in Baotou requires much stronger motors to drive the large heavy capsule set. A fully-loaded five-capsule set will weigh about 3 times of the previous design for the 70m-long prototype pipeline system. There are several solutions to improve the motor performance, such as wider, thicker, and longer permanent magnets.

TABLE 3
COMPARISON OF THE MAX PROPULSION FORCES OF ONE CAPSULE WITH SIX WAVELENGTHS OF 1.25 CM THICK MAGNET ARRAYS WITH DIFFERENT WINDING WIDTHS

Winding width	Max propulsion force (N/A)	Force percentage relative to 0.6m wide winding	Winding percentage relative to 0.6m wide winding	Power loss percentage relative to 0.6m wide winding
0.6 m	1.8	100%	100%	100%
0.7 m	1.915	106.4%	116.7%	103.1%
0.8 m	1.994	110.8%	133.3%	108.5%

TABLE 4
COMPARISON OF THE MAX PROPULSION FORCES OF ONE CAPSULE WITH SIX WAVELENGTHS OF MAGNET ARRAYS WITH DIFFERENT MAGNET THICKNESSES (0.6 METER WIDE MOTOR WINDINGS)

Magnet thickness	Max propulsion force (N/A)	Force percentage relative to 1.25 cm thick magnets	Magnet percentage relative to 1.25 cm thick magnets
1.25 cm	1.8	100%	100%
2 cm	2.62	145.6%	160%
2.5 cm	2.62	145.6%	160%

Based on the previous design for prototype capsule with six wavelengths of 0.45 m wide and 1.25 cm thick magnet arrays, Table 3 compares the simulation results of the max propulsion force of one capsule with different winding widths. The max propulsion force will increase with the motor winding width. In comparison with 0.6 m wide case, however, a wider 0.7 m winding can get only 6.4% more max propulsion force, much less than the winding increment of 16.7%. Therefore, the reasonable improvement is to increase width of the magnet array from 0.45 m to 0.55 m to match the current 0.6 m wide motor winding. The max propulsion force will be increased approximately linearly with the winding width by (0.55-0.45)/0.45=22.2%. For a fixed motor winding width of 0.6 meter, Table 4 shows the max propulsion force of one capsule with six wavelengths of magnet arrays with different magnet thicknesses. In comparison with the 1.25 cm thick magnet array, the 2 cm thick magnet array case will get 45% more propulsion force, and a double thick (2.5 cm) magnet array can get 71.2% more force, but they require 60% and 100% more magnet, respectively.

The new design for current heavy capsules is to reduce the coupling between two capsules by half and make the capsule body longer so as to put 8 wavelengths of magnet arrays on its bottom, which is about 1.333 times of the 6-wavelength magnet arrays for each previous capsule. The propulsion force is proportional to the wavelength number of magnet arrays engaged with linear motor windings, so on average, the max propuslion force will be increased by 33.3%. If combined with the above two improvements on magnet width (0.55 m) and thickness (2.5 cm), the max propulsion force will be $1.222 \times 1.712 \times 1.333 = 2.79$ times of previous design, which can closely match the capsule weight increasement. However, the larger magnet arrays will present the motor windings with 2.79 times back electromotive force (EMF). Due to the voltage limitation on motor drives, the new standard pipeline linear motor module will only use standard 3m-long motor windings.

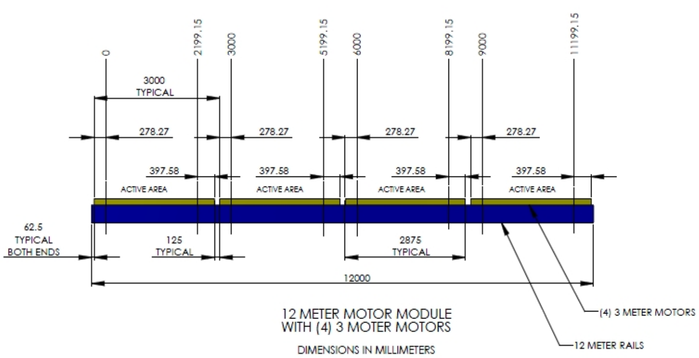

Figure 5. One standard 12m-long motor module with four 3 m motor windings.

As shown in Figure 5, one standard 12m-long motor module can be fitted with four 3m motor windings. The actual length of 3m-long motor winding is about 2,875 mm so that there is a 125 mm gap between two nearby motor windings which can be used for the cable connection to the motor drives. Typically for the new coal-carrying pipeline system in Baotou, one standard 12m-long motor module will carry 1 to 4 standard 3m-long motor windings. For some cases on the flat ground, only one 3-m motor winding in each 12 m standard motor module would have enough power to propel the 5-capsule set.

4 SPEED CALCULATION AND MOTOR DRIVES FOR THE DEMONSTRATION SYSTEM

The pipeline is composed of standard 12m-long pipe modules, and accordingly, the linear synchronous motor winding consists of 3m-long 3-phase coils; one to four 3 m long coils can be connected within a 12 m long pipe module.

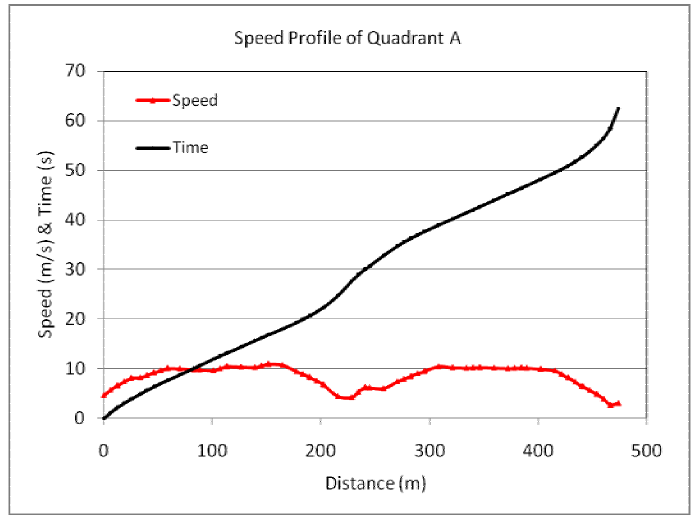

Figure 6. Speed profile of Quadrant A.

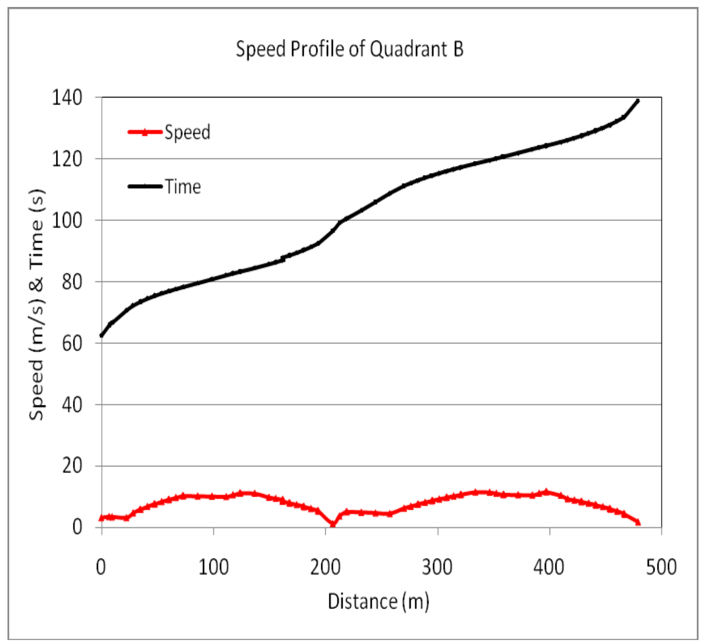

Figure 7. Speed profile of Quadrant B.

Figures 6-9 show the designed speed profile of Quadrant A, B, C, D of the 1 km Baotou Demonstration Line, respectively. The design speed of the capsule set for the pipeline is 10 m/s. Seen from Figure 6, the capsule set will do the acceleration in the beginning, and slow down in the middle when it passes through the hill upslope because there is not sufficient propulsion force to maintain the speed. The capsule set will decelerate before it goes through the U-turn with the average speed of 3 m/s. It takes about 60 seconds for the capsule set to travel through the outbound pipeline (Quadrant A) with the length of 475 m, so the average speed on Quadrant A is about 8 m/s. As shown in Figure 8, the speed profile of return pipeline (Quadrant B) looks similar to the

Quadrant A, spending 75 seconds for 480 m, and the average speed is about 6.5 m/s. Both unload and load stations (Quadrants C and D) are low speed regions. Considering the 10 seconds for either loading or unloading the materials, each quadrant takes 60 seconds to travel about 120 m distance, so the average speed in low-speed regions is about 2 m/s, which is much less than the 3.5 m/s speed limit for the bend radius of 7 m. The capsule set will take totally 260 seconds to travel the full cycle length of 1.2 km, and the average speed for one cycle is about 4.6 m/s.

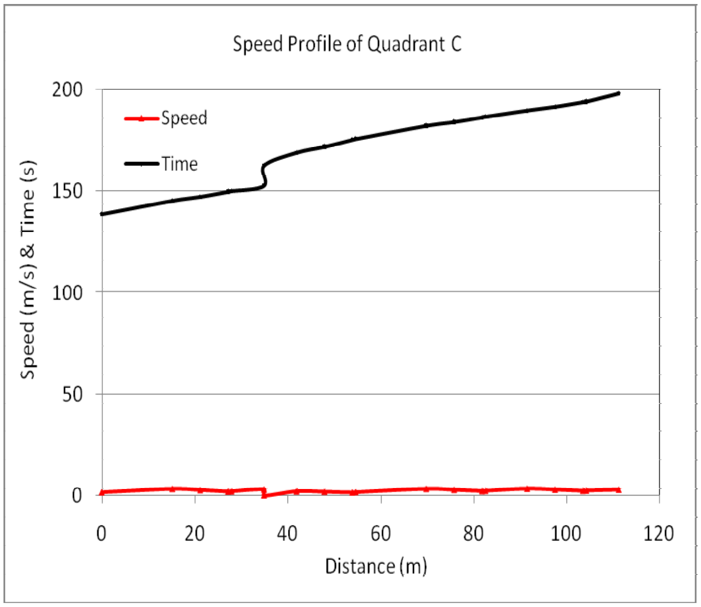

Figure 8. Speed profile of Quadrant C.

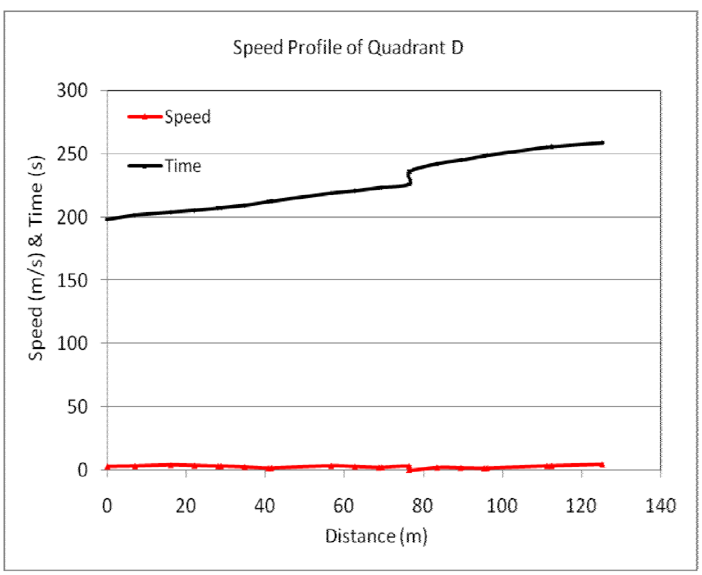

Figure 9. Speed profile of Quadrant D.

The current, voltage, and power of each motor winding can be calculated according to the designed speed profile. As shown in Figure 1, the 1km-long Baotou demonstration pipeline has totally 100 pipe modules with 200 3m-long motor windings. Table 5 lists the current, voltage and power range of 200 motor windings. 84 motors (about 40% of total motors) work around the nominal current of 40 A. The voltage of one 3m-long motor winding varies largely from 60 V to 300 V, and each motor winding can be controlled by one motor drive. However, two 3m-long motor windings with low voltages can be easily connected in series to be a 6m-long winding using only a larger motor drive in order to save one motor drive. The max power of 3m-long motor windings is 45 kW with the motor current of 50 A.

TABLE 5
THE CURRENT, VOLTAGE AND POWER RANGE OF 200 3M-LONG MOTOR WINDINGS

Motor current range (A)	Motor quantity	Voltage range of 3 m windings (V)	Peak power of 3 m windings (kW)
0-9	12	60-250	6
10-19	36	60-120	5
20-29	36	100-300	30
30-39	20	200-280	35
40-49	64	130-300	45
50	32	170-280	45

5 STOPPING AND RESTARTING OF 5-CAPSULE SETS

The 1 km Baotou Demonstration Line will demonstrate all the operations necessary for a commercial system, including the safe stopping over the motor using the battery backup power system after a power failure, and a restart after the power system has been recovered. As shown in Figure 5, one standard 12m-long pipe module can carry 1 to 4 standard 3m-long motor windings, and the motor windings are uniformly distributed along the pipeline so that no 5-capsule set will ever stop where it has no contact with at least a portion of a motor winding. However, as a precaution, the system would ordinarily be shut down following a power failure, in a controlled manor, so that each 5-capsule set has full engagement with at least one pre-selected 3m-long motor winding.

Based on the speed profile designed for each quadrant of demonstration line, the stopping distance, time, and energy of one five-capsule set from any point of pipeline after a power failure can be calculated. The simulation results indicate that the initial two 5-capsule sets for the demonstration line will need an external 1MJ, 300kW battery backup power system to be safely stopped over the desirable motors.

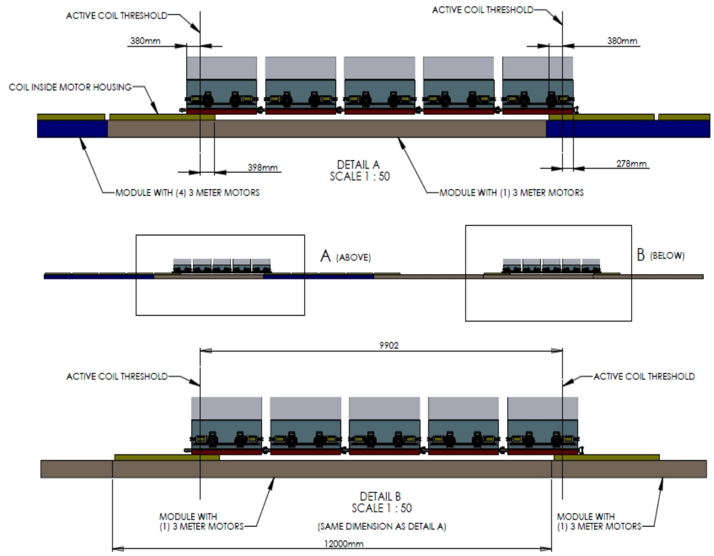

Figure 10. One train set of 5 capsules overlap with 12m-long motor modules.

In the previous design for a prototype pipeline system, in case a capsule set cannot stop over the motor after a power failure, the capsule tug rescue system can drive the capsule to the closest available motor. Figure 10 shows one train set of 5 new heavy capsules overlap with 12m-long motor modules. No matter whether a 12m-long pipe with only one 3m-long motor winding on the flat ground or four motor windings for hill slopes, a 10.8m-long five-capsule set will overlap with at least one motor winding everywhere, easing the restart following a power failure. One standard 12m-long motor module will only need one 3m-long motor winding on the flat ground. Once the train set is moving, the train set will overlap with more motor winding up to four 3 m motor windings to reduce the required propulsion current dramatically. Therefore, the new 3m-long motor winding design for standard 12m-long motor modules can save the capsule tug rescue system, and the pipeline system can be easily restored after a power failure.

6 CONCLUSIONS

We have completed the preliminary design of the innovative linear motor driven pipeline transportation system. The initial commercial demonstration of a Magplane pipeline in Baotou, China will be a 1km-long coal-carrying pipeline system with a design transportation capacity of 10 Mega-tons per year with a large potential to replace trucks and railways at reduced operating cost and power consumption. The new pipeline system will use two new C-channel side rails to support heavier coal-carrying capsules. The pipeline is composed of standard 12m-long pipe modules made with 1 to 4 standard 3m-long motor windings so that a 5-capsule set will overlap with at least one motor winding everywhere in order to save the capsule tug rescue system after a power failure. Upon completion of the 1 km demonstration pipeline in 2012, the first 12km-long commercial line will be constructed to carry coal ores in Erdos, China.

7 REFERENCES

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