An Unmanned, Battery-Operated TBM Tunneling Scenario

for the 34km VLHC Injector Tunnel at Fermilab

******** 10/6/1998 DRAFT *********

G. William Foster

October 6, 1998

ABSTRACT

A simplified and potentially inexpensive tunneling scenario for the 34km circumference VLHC Injector Accelerator tunnel is described. The circular tunnel is to be excavated in two 17km drives from a single point on-site at Fermilab. The tunnel depth is ~150m, and the tunnel diameter is 8-12ft. diameter. No underground shift personnel will be present during routine tunneling operations, but only during scheduled (and unscheduled) maintenance. Excavation takes place via a standard, remotely piloted Tunnel Boring Machine (TBM) head. The tunnel is completely unimproved, with no conveyor, electrical, water or rail service. All material access and muck removal is to be done via two 3km sloped tunnels ("transfer lines") which are later used to deliver beam to the accelerator. All TBM support takes place via the delivery of 40m long "cartridges" which provide for muck removal, water supply, and battery power for one hour of operation. The cartridges are delivered via a single unmanned rubber-tired battery powered flatbed vehicle which shuttles once per hour between the TBM and the surface. The TBM can accept cartridges at either of two side-by-side locations, so that power, water, and muck storage will be continuously available. This scenario minimizes or eliminates the costs associated with underground crews, electrical installation, ventilation, water supply, and railway installation. A possible demonstration project is discussed.

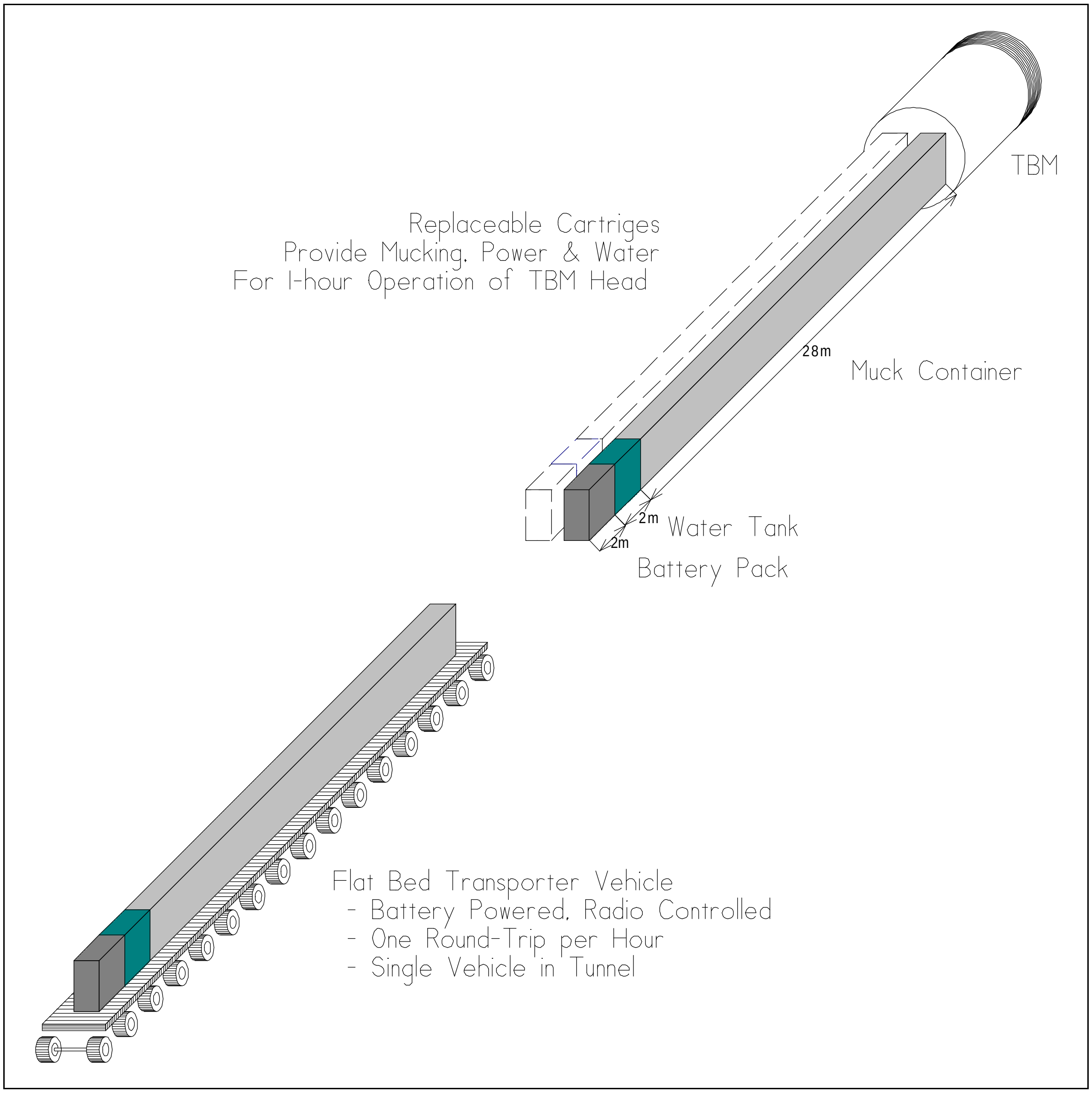

Fig. 1 – Automated tunneling concept based on replaceable cartridges for TBM support. Cartridges contain power, water, and muck storage for 1 hour (3 meters) of tunneling. The TBM operates on one cartridge while the other is replaced. A battery-powered radio-controlled flatbed transporter vehicle shuttles replacement cartridges to the surface once per hour. The system requires no conveyors, railways, electrical power lines, or water pipes.

INTRODUCTION

The single highest-payoff activity for reducing accelerator tunneling costs is the elimination of in-tunnel labor. For example, the Kenny Const. Co. estimate for the 34km VLHC tunnel was based on two 20-person crews underground 24 hrs/day in support of two TBM's. More than 50% of the direct project cost was labor. On the other hand, the TBM head itself does not require an underground crew. Recent Robbins TBM designs have been 100% electronically remotely operated (though typically by an operator in the tunnel). With appropriate remote control and monitoring, it is reasonable to expect most TBM maintenance to be confined to a single scheduled maintenance shift per week. The labor requirement comes almost entirely from TBM support activities such as conveyor belt installation and maintenance, railway operation and extension, extension of electrical lines and lighting, installation of water pipes, ventilation hose, etc. This paper explores a scenario which reduces or eliminates these items.

The parameters for tunnel diameters of 8 ft., 12 ft., and 5ft. are given in Appendix A. These are based on an assumed peak TBM advance rate of 3m/hour and an average rate of 2m/hour (66% availability), resulting in a 15-month tunneling time.

TBM SUPPORT CARTRIDGES

The central concept (fig. 1) is the use of self contained TBM Support Cartridges which contain a muck box, a water tank, and a lead-acid battery pack to provide everything the TBM needs for 1 hour (3 meters) of tunneling. Since two of these can be plugged in side-by-side (whereas the TBM needs only one to operate), the TBM can operate continuously while the "used" cartridge is transported out and a fresh cartridge is returned. The cartridge is ~32m long assuming that the cross section of the cartridge takes ~1/6 of the cross sectional area of the tunnel. Of this, 28m are for muck box, 2m for the battery pack, and 2m for the tank which supplies water for motor cooling and dust control. Other consumables (lubrication oil, disc cutters, etc.) will be furnished during weekly maintenance.

BATTERY POWER

An unconventional feature of this scheme is the use of battery power to supply the TBM. A first question is whether the size and weight of the battery pack will be excessive. A conventional deep-discharge lead-acid battery (the type normally used in battery-powered mine locomotives, submarines, etc.) has a specific energy density of 30 kWh/ton. In comparison, the specific energy of excavation of Galena-Platteville Dolomite is approximately 5 kWh/ton. One way to think about this is that 1 ton of batteries can excavate 6 tons of rock. Thus the additional hauling effort to bring batteries to and from the cutting face is a small fraction of that required to haul the muck out. The batteries are also denser and more compact than the muck. This can be seen by the fact that batteries comprise only 2m out of the 32m length of the cartridge.

A second question is whether the battery power is itself is inherently expensive. Industrial lead-acid batteries are a mature and competitive industry and the costs are well known. The cost of Valve-Regulated Lead-Acid batteries (VRLA's) is approximately \$150/kWh installed capacity. However this cost gets amortized over 1500 charge/discharge cycles before the battery is thrown out after it degrades 80% of rated capacity. (Since about 6000 total charge/discharge cycles will be needed for each 17 km drive, most of the batteries will be fully consumed). In this case the materials cost for batteries is \$0.10/kWh delivered to the load. When one factors in the 70% electrical efficiency of the batteries and charger, delivering power through batteries increases the cost of electrical power from ~$0.10/kWh to $0.25/kWh. This remains a small fraction of the overall tunneling cost, corresponding to $25/meter for an 8-foot diameter tunnel.

A third question is safety. There is a large body of experience in using Lead-Acid batteries in submarines and underground, and it is understood how to make them safe and reliable. Lead-acid batteries evolve quantities of hydrogen only during rapid charging, which will take place above ground. The electrical connections are made by plugging the cartridges into the TBM via remote control with no people present in the tunnel.

POWER CONVERSION

There are a number of options for power conversion from battery power to motor power in the tunnel. The most straightforward is to purchase a ~200kW inverter similar to ones used in uninterruptable power supplies. The unit can be conservatively rated so that it can supply the large starting torque to the motors. The batteries themselves are capable of delivering very large peak power (more than ten times their rated continuous power) for small periods.

Another option is direct conversion of battery power to operate brushless DC motors. These are simple and reliable motors with one moving part, and are used on tank turrets, etc. This will provide the most efficient power conversion, but will require another low-power inverter to supply on-board computers, electronics, etc.

The electrical coupling between the cartridge and the TBM must be made rugged and reliable. One interesting possibility here is to use an inductive coupler similar to those developed for recharging battery-operated cars. Because they rely on magnetic coupling between the source and load, there are no exposed voltages, etc.

TRANSPORT VEHICLE FOR CARTRIDGES

Only a single transport vehicle (fig.2) is in the tunnel at one time, and no sidings or vehicle passing must be allowed for. Therefore a rubber-tired battery-operated remote-controlled flatbed carrier will do the job. The vehicle can operate in a completely unimproved tunnel, with its wheels partway up the sides of the tunnel and a rubble-strewn creek flowing between its wheels.

A comparable vehicle manufactured by Brookville Mining Equipment Corporation (BMEC) is shown in fig.3. In preliminary discussions with Larry Conrad, an engineer at BMEC, he confirmed that the general parameters (4 tons per axle, 25 mph maximum speed, battery operation for 10-mile round trip) were reasonable design goals. They have experience incorporating radio controls into these vehicles, or the control system could be subcontracted by Fermilab.

The vehicle does not need to steer. There is some concern that the circular cross section of the tunnel will cause the vehicle to ride up on the tunnel walls. If this is a problem, it could be controlled by adding a small amount of steering capability to the front or rear wheels. Position in the tunnel could be sensed using the tilt of the vehicle.

According to BMEC, the reliability of battery electric vehicles in mines is excellent. Transporter vehicles are used continually (i.e. they are in use and moving more than half the time) during mining operations. Transporters with a large number of independently powered axles can allow one axle to fail and the transporter will still function.

If three transporters are purchased (two in use continually in the mine, and a third spare or undergoing maintenance) then the TBM can expect a very high availability for muck removal, power, and water. The service lifetime required is 40,000 miles for each of the three transporters. This is within the range of standard automotive technology.

REMOTE CONTROL

Eliminating labor in the tunnel requires that the Cartridge Transporter be remotely piloted. Radio links based on "leaky cable" technology have been in use for several years in mines. These links transmit voice, video and digital data. They require stringing an RF cable which must be extended periodically. For example, if the cable was extended during the weekly maintenance shift (corresponding to 300m of tunnel advance) then both the Transporter and the TBM would be in continuous contact and the surface.

The number of control points in the system is quite small. The transporter has only a speed and direction control, with automatic stopping at each end of the run. The cartridge changing system at the TBM needs only a 2-way "switch" and a motor drive to eject or inject cartridges.

The cartridge loading and unloading system on the surface could be (for example) an automated overhead crane executing pre-programmed sequences. A single crane could service transporters from both tunnels. Similar crane systems are used in automated materials-handling yards and warehouses. On attractive scenario is to accumulate filled "muck boxes" over a 24-hour period, and emty them into trucks during the day shift.

It is anticipated that the routine remote-control operation of the TBM and transporter could be incorporated into the routine shift duties of the personnel in the Fermilab Main Control Room. The level of technological expertise required is well below that required to operate the cryogenic systems, the safety interlock systems, and the accelerator itself. As in the case of the accelerators, there would computerized monitoring of operations and experts "on-call" to handle abnormalities.

MAXIMUM SPEED AND EQUIPMENT SAFETY ISSUES

The scenario outlined here (17 km tunnel drives, 1-hour cartridge replacement time) requires a maximum speed of 25 mph for the cartridge transporter. However, the scenario does not depend critically on the transporter speed. If the maximum safe speed for the transporter turns out to be half of that (12.5 mph) then the project completion time is only increased by 25%. Alternatively the muck box and transporter could be made longer, corresponding to a 1½-2 hour replacement period. However, it is worth pushing on the transporter speed during R&D since this will permit even longer tunnel drives for the larger (500 km circumference) accelerator being envisaged for the future.

The stopping distance for a rubber-tired vehicle at 25 mph (40 kph) is ~25 meters. The stopping time is ~5 seconds. A sonar or camera-based based system which detects large objects (e.g. rock falls) at least 25m ahead would prevent damage to the vehicle. A "cow-catcher" which directs rubble from small rock falls away from the wheels and into the creek at the bottom of the tunnel would permit the transporter to continue operations until the weekly maintenance shift cleans up. Alternatively, a small form-fitting scoop may be installed at the ends of the transporter to performed limited cleanup.

Potholes in the tunnel floor are less of a problem since a many-axled transporter bridges over them. If necessary, the computer controlled system could maintain a map of these potholes and reduce speed at the affected locations.

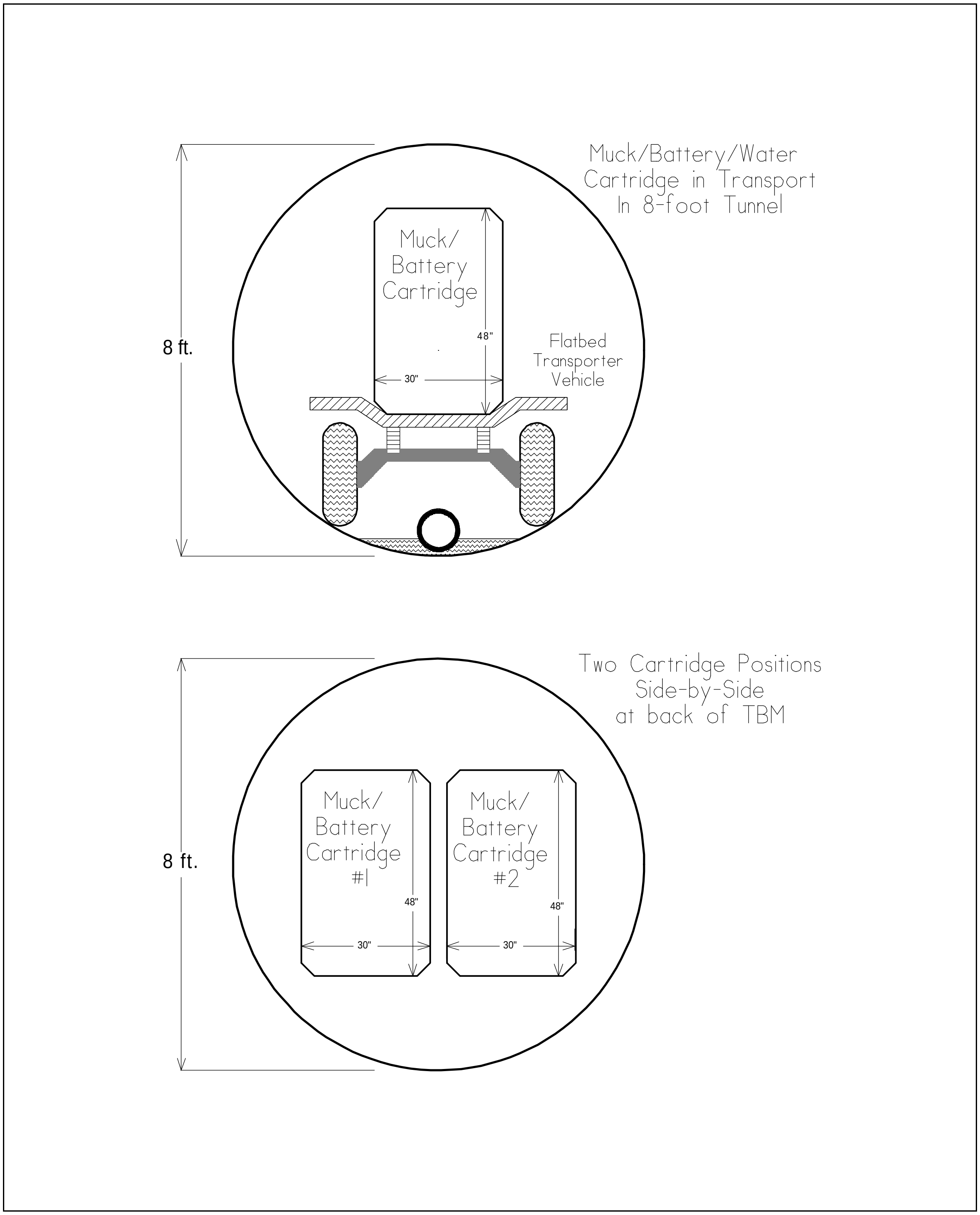

Fig. 2 – Cross sections of replaceable TBM Support Cartridges on the flatbed transporter and in use at the TBM. The empty and full battery/muck boxes must pass each other at the TBM but not during transport.

Brookville Mining Equipment Corporation

RUBBER TIRED VEHICLES

Custom Designed & Powered By

Diesel - Battery – Trolley - Battery / Trolley Combination

Personnel Carriers

- **2 To 17 Person Capacity**

Haulage Tractors

- **8 To 35 Ton**
- **4 - Wheel Steering**
- **Coordinated / Crab Steering**

Fig. 3 – Rubber tired vehicles from the Web Page of Brookville Mining Equipment The web address is: http://www.bmec.com/

SO, WHAT'S MISSING?

Rock bolting: automate. What is frequency of "problems" in our Dolomite?
Grouting: remote control
Survey: setup lasers on weekly maintenance shifts
Ventilation: small high-pressure line ~1m^3/sec installed in 300m lengths weekly. Non-problem once complete circumference of tunnel completed.
Water Removal: sumps every 300m with HDPE pipe in creek at bottom of tunnel. Drag in 300m lengths of HDPE pipe on weekly maintenance shifts.
Slip Lining: (optional) after completion of tunnel loop when manned safety OK.
TBM removal at end of drive: ?

SCALING TO LONGER TUNNEL DRIVES

The ultimate 50x50 TeV VLHC requires a 500 km circumference tunnel with a cryogenic plant and surface access every ~70km. This could be tunneled, for example, from eight locations with two 35 km drives from each location. This requires scaling the cartridge system by a factor of two (in drive length) compared to the 34km tunnel.

A primary advantage of the "cartridge" approach is that it scales gracefully to longer tunnel drives. This is in contrast to conveyor-belt based systems. As mentioned above, the project completion time does not depend strongly on the speed of the cartridge transporter.

Two times longer cartridges could be used to support the longer time between changes needed for 2x longer tunnel drives. The speed of the transporter could also be increased. Sidings to allow the transporters to pass each other underground could be developed. Or finally, one could simply decree that 50% availability of the TBM support is acceptable for the final lengths of the drive.

DEMONSTRATION PROJECT

It is possible to consider a relatively inexpensive demonstration project for the "Cartridge" technique based on a small diameter (4-5ft) microtunneling TBM. Jim Friant described impressive performance for a 4ft(?) diameter TBM equipped with mini-disc cutters and a 40hp(?) motor in a recent letter-to-the-editor in a tunneling magazine. The battery-power system and a cartridge-transporter based system for such a small diameter could be produced for a few hundred k$. The surface costs could be minimized by starting the tunnel in an existing quarry such as the Conoco Dolomite quarry in North Aurora (just south of Fermilab). It is possible that such a demonstration project might be of interest to microtunneling firms, since the cartridge system avoids the down-hole labor of "threading the necklace" of each new pipe segment with the power cables and slurry hoses.

Appendix A - BATTERY POWERED TBM EXCAVATION

TUNNEL PARAMETERS			
Tunnel Diameter	**8.00 ft.** = 2.44 m.	**12.00 ft.** = 3.66 m.	**4.00 ft.** = 1.22 m.
Cross Section	4.7 m^2	10.5 m^2	1.2 m^2
Number of Drives	2	2	2
Drive Length	17 km.	17 km.	17 km.
Tunnel Depth	150 m.	150 m.	150 m.
Invert	none	none	none
Conveyor	none	none	none
Railways	none	none	none
Sidings	none	none	none
Electrical	none	none	none
Water Pipes	none	none	none
TBM	(J. Roby, Robbins TBM)		
Peak Advance Rate	3.0 m/hr.	3.0 m/hr.	3.0 m/hr.
Average Advance Rate	2.0 m/hr.	2.0 m/hr.	2.0 m/hr.
Energy Consumption Per Meter	67 kWh/m	150 kWh/m	17 kWh/m
Peak Power	200 kW	450 kW	50 kW
Water Consumption	2.0 m^3/hr.	4.5 m^3/hr.	0.5 m^3/hr.
MUCKING			
Excavated Rock Volume (peak)	14.0 m^3/hr.	31.5 m^3/hr.	3.5 m^3/hr.
Expansion Factor for Chips	2	2	2
Muck Volume	28.0 m^3/hr.	63.0 m^3/hr.	7.0 m^3/hr.
Rock Density	2.65	2.65	2.65
Muck Weight	37.1 tonnes/hr.	83.5 tonnes/hr.	9.3 tonnes/hr.
MUCK BOXES			
Filling Time	1.0 hr.	1.0 hr.	1.0 hr.
Volume	28.0 m^3	63.0 m^3	7.0 m^3
Cross Section	1.0 m^2	2.2 m^2	0.2 m^2
Length	28.2 m	28.2 m	28.2 m
Weight (empty)	4 t.	6 t.	2 t.
Weight (full)	41 t.	90 t.	11 t.
BATTERY USAGE FOR EXCAVATION			
Battery Type	lead-acid	lead-acid	lead-acid
Specific Energy	30 kWh/tonne	30 kWh/tonne	30 kWh/tonne
Discharge Fraction	0.80	0.80	0.80
Discharge Time	1.0 hr.	1.0 hr.	1.0 hr.
Power Required	200 kW	450 kW	50 kW
BATTERY PACK PARAMETERS			
Battery Weight	8.3 t.	18.8 t.	2.1 t.
Battery Density	4.	4.	4.
Battery Pack Volume	2.1 m^2	4.7 m^2	0.5 m^2
Battery Pack Cross Section	1.0 m^2	2.2 m^2	0.2 m^2
Battery Pack Length	2.1 m.	2.1 m.	2.1 m.

Tunnel Diameter:	**8.00 ft.**	**12.00 ft.**	**4.00 ft.**
CARTRIGE PARAMETERS			
Cross Section	1.0 m^2	2.2 m^2	0.2 m^2
Muck Box Length	28.2 m.	28.2 m.	28.2 m.
Water Tank Length	2.0 m.	2.0 m.	2.0 m.
Battery Pack Length	2.1 m.	2.1 m.	2.1 m.
Overall Length	32.3 m.	32.3 m.	32.3 m.
Weight (inbound)	14.4 t.	29.3 t.	4.6 t.
Weight (outbound)	51.5 t.	112.9 t.	13.9 t.
TRANSPORTER PARAMETERS			
Type	flatbed truck	flatbed truck	flatbed truck
Power	Battery	Battery	Battery
Number per Tunnel	1	1	1
Round Trips Required per Drive	5667	5667	5667
Average Round Trip Length	17 km.	17 km.	17 km.
Total Mileage per Drive	96,333 km.	96,333 km.	96,333 km.
Operator	Remote Cntrl.	Remote Cntrl.	Remote Cntrl.
Length	32.3 m.	32.3 m.	32.3 m.
Sagitta in Tunnel (5km radius)	0.03 m.	0.03 m.	0.03 m.
Articulation	none	none	none
Weight (unloaded--WAG)	10.0 t.	22.5 t.	2.5 t.
Weight (inbound)	24.4 t.	51.8 t.	7.1 t.
Weight (outbound)	61.5 t.	135.4 t.	16.4 t.
Number Of Axles	14	17	10
Weight Per Axle	4.4 t.	7.9 t.	1.7 t.
Loading Time (each end)	5 mins.	5 mins.	5 mins.
Travel Time (each way)	25 mins.	25 mins.	25 mins.
Travel Speed Req'd (average)	20 kph	20 kph	20 kph
Travel Speed Required (max)	41 kph	41 kph	41 kph
TRANSPORTER BATTERY USAGE			
Rolling Coefficient of Friction	0.04	0.04	0.04
Max Distance Traveled	17 km.	17 km.	17 km.
Max Rolling Energy (inbound)	45 kWh	96 kWh	13 kWh
Max Rolling Energy (outbound)	114 kWh	251 kWh	30 kWh
Payload Lift (outbound-inbound)	15 kWh	34 kWh	4 kWh
Max Energy Consumption per trip	174 kWh	381 kWh	47 kWh
Avg. Energy Consumption per trip	95 kWh	207 kWh	26 kWh
Battery Weight for Transporter	7.3 t.	15.9 t.	2.0 t.
BATTERY ECONOMICS	(Richard Bendert, GNB Industrial Battery,691-7878)		
Battery Cost	$150 /kWh	$150 /kWh	$150 /kWh
Lifetime Discharge Cycles	1500	1500	1500
Amortized Battery Cost	$0.10 /kWh	$0.10 /kWh	$0.10 /kWh
Wall Power Cost	$0.10 /kWh	$0.10 /kWh	$0.10 /kWh
Energy Efficiency (charger)	0.90	0.90	0.90
Energy Efficiency (battery)	0.70	0.70	0.70
Cost of Electricity from Battery	$0.26 /kWh	$0.26 /kWh	$0.26 /kWh
Excavation Energy per Meter Tunnel	67 kWh/m	150 kWh/m	17 kWh/m
Transporter Energy per meter Tunnel	32 kWh/m	69 kWh/m	9 kWh/m
(Battery + Electricity) cost/meter	$25.41 /m	$56.69 /m	$6.51 /m

APPENDIX B – THE VLHC PROJECT

Fermi National Accelerator Laboratory, located in Batavia Illinois in suburban Chicago, is the owner and operator of the world's most powerful particle accelerator, 6km circumference superconducting Tevatron. As part of it's ongoing mission to further research at the frontiers of particle physics, planning has begun for a next generation of accelerators. The most advanced of these plans is tentatively dubbed the Very Large Hadron Collider, or VLHC. This project will require much longer tunnels, eventually as large as 500km. These tunnels must be bored at depths 50-150m underground to avoid surface disturbance. This project will take advantage of the favorable and well understood dolomite geology of northern Illinois, which is already home to 160km of tunnels for the TARP (or Deep Tunnel) reservoir project in Chicago.

The first stage of this project requires construction of a pre-accelerator (or Injector) machine of circumference approximately 34km. Part of function of this first stage is to serve as a proof-of-principle for the advanced techniques in particle accelerators, superconducting magnets, and tunneling. An equally important goal, in light of the painful experience with the Superconducting Supercollider in Texas, is to demonstrate acceptably low construction costs for machines of this type.