Fabrication and Testing of Full Scale Components for the 2nd Gen. Maglev-2000 System

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ABSTRACT: Fabrication and tests of full scale M-2000 components – superconducting quadrupole magnets, aluminum loop guideway panels, monorail guideway beam and vehicle body – are described. The M-2000 superconducting quadrupole enables levitated travel on monorail and planar guideways, including existing RR tracks, high speed electronic switching to off-line stations, and Earth level magnetic fields in passenger cabins. Two quadrupoles were successfully tested using liquid He cooled NbTi superconductor operating at 600,000 amp turns. Measured magnetic fields and forces agreed with predictions for the nominal gap of 4 inches between the Maglev vehicles and guideway. Full scale aluminum loop guideway panels that provide vertically and horizontally stable levitation and propulsion were also fabricated and successfully tested. A 72 foot long monorail guideway beam and 60 passenger vehicle chassis and fuselage were also fabricated. The next step, the assembly of M-2000 components into vehicles for testing on an operating guideway is discussed.

1. INTRODUCTION

The Danby-Powell concepts for using superconductors to levitate and propel high speed vehicles began in the early 1960's. In 1963, Powell proposed the Magnetic Road,[1] a system in which vehicles were magnetically levitated by the interaction between currents carried in superconducting cables on a guideway and currents in loops on a moving vehicle.

While technically feasible, the cost and refrigeration power for the superconducting track was not practical. Danby then proposed using superconducting magnets on a moving vehicle to induce currents in a sequence of normal aluminum loops located on the guideway. The magnetic interaction between the superconducting magnets on the vehicles and the induced currents in the guideway loops provided the forces required to levitate the vehicle.

Working collaboratively, Danby and Powell published their concept of a superconducting Maglev system in 1966[2] and obtained the original patent on superconducting Maglev in 1969[3]. Subsequent publications[4][5][6][7][8][9][10] developed the concept in more detail, including the superconducting Linear Synchronous Motor[11], in which a small AC current in a sequence of aluminum guideway loops magnetically interacted with the superconducting magnets in the vehicle to propel it along the guideway at a fixed speed determined by the frequency of the AC current. For their work on superconducting Maglev, Danby and Powell were awarded the Franklin Institute Medal for Engineering in April, 2000.

Following the publication of the superconducting Maglev concept, a number of Maglev development programs started in various countries, including Japan, German and the U.S. Japan chose to develop the Superconducting Maglev System based on the Danby-Powell inventions. Their 1st generation system is now operating successfully at Yamanashi in Japan. (Figure 1) It holds the World ground transport speed record at 361 mph, and has carried well over 50,000 passengers. A 300 mile Maglev route between Tokyo and Osaka, to be completed by 2025,

Figure 1 View of Japn Railways Superconducting Maglev Guideway and Vehicle System

is under consideration. Germany has developed a different 1st generation maglev system, termed Transrapid, with 1st generation systems now operating in Germany and China. It is based on the use of conventional electromagnets on the vehicle, which are attracted upwards to iron rails on the guideway, levitating it. To maintain the ~ 1 centimeter gap between the vehicle electromagnets and the iron rails, it is necessary to rapidly servo control the currents in the windings on the vehicle's electromagnets.

In contrast, the superconducting Maglev System is inherently strongly stable, with magnetic restoring forces that automatically oppose any external force (e.g., winds, curves, etc.) that would act to displace the vehicle from its equilibrium suspension position. The gap between vehicle and guideway is substantially greater for superconducting Maglev than that for electromagnetic Maglev, typically ~ 10 cm vs. ~1 cm. The much larger gap enables the guideway to be built with less demanding construction tolerances, helping to reduce the cost of construction.

Following the 1966 Danby-Powell publication the U.S. initiated R&D programs on superconducting Maglev, but stopped in the early 1970's, on the belief that existing U.S. transport systems – autos, trucks, airplanes, and conventional rails – would be sufficient into the indefinite future. U.S. interest in Maglev revived in 1989 when Senator Daniel Patrick Moynihan sponsored legistlation for a 750 million dollar R&D program on Maglev. His legislation passed the Senate, but was killed in the House of Representatives. Senator Moynihan's vision was for a U.S. National Maglev System to be built on the rights-of-way along the Interstate Highway System.(12)

Subsequently, legislation was passed for a program to assess the potential for deployment of a Maglev demonstration routs of 20 miles or greater length to be built in the U.S. Seven routes were selected for study. Six of these studies proposed building the German Transrapid system as a demonstration. The seventh study, which was carried out by the Maglev 2000 of Florida Corporation(13), used the new 2nd generation superconducting Maglev system developed by Powell and Danby. The proposed 20 mile route ran from the Canaveral Seaport to the Titusville regional airport, with an intermediate station at the Kennedy Spaceport visitor center. After initial operation of the demonstration route, it was proposed to add a 30 mile extension to the Orlando International Airport and Disney World.

As part of the Florida study, 2nd generation full scale Maglev components were fabricated and tested to determine performance and validate cost projections. The components included superconducting quadrupole magnets, guideway loop panels, a 72 foot long monorail guideway beam, and the undercarriage and fuselage for a urban/suburban vehicle. The design and fabrication of these components is described in more detail later in the paper.

Following completion of the Phase 1 sites of the 7 Maglev routes, two routes, Pittsburgh and Baltimore-Washington, were selected for further study. Both routes proposed using the German Transrapid system.

2. THE 2ND GENERATION MAGLEV-2000 SYSTEM

The 1st generation Maglev systems, while technically successful, have limitations that to date have prevented implementation of a large scale. Two factors are of particular importance in limiting their implementation, particularly in the U.S.

First, the construction cost of the guideway is very ;high, $50 million dollars or more per mile. This is much more than the cost of High Speed Rail (HSR) systems which is on the order of 20 to 30 million dollars per mile. While Maglev offers shorter travel times than HSR, its advantages are not great enough to justify the higher construction cost.

Second, the 1st generation Maglev systems only carry passengers. While very useful in densely populated areas like Europe and Japan, passenger only systems are of less utility in lower population density large countries like the United States. In the U.S. the big transport outlays are for intercity trucks (over 300 Billion dollars annually) not intercity air passengers (60 Billion dollars per year) and intercity rail passengers (only 3 Billion dollars per year.) Passenger only systems in the U.S., whether they are Maglev or High Speed Rail, will require major government financing for construction and continued large subsidies for operation and maintenance. Because of America's very large governmental debt, both State and Federal, it is unlikely that major government financing is possible. To be implemented, Maglev routes will have to attract private investment. To achieve this, they must be profitable, with a relatively short payback time on invested capital, e.g. significantly shorter than a decade.

The 2nd generation Maglev-2000 system is specifically designed to address these two factors. First, the guideway construction cost is projected to be only about 25 million dollars per mile, a factor of 2 or more lower than 1st generation systems. To achieve this, low cost prefabricated monorails are used for most of the elevated guideway construction. Figure 2 shows an artist's view of a Maglev-2000 passenger vehicle on the monorail guideway.

Figure 2 Artist's Drawing of Maglev-2000 Vehicle on Monorail Guideway

The prefabricated monorail beams would be mass produced in factories, with their guideway loop panels, sensors, electronic equipment, etc. attached to them at the factory. The beams and piers would then be transported by truck or rail to the construction site, where they would be quickly erected on pre-poured concrete footings or pilings, using conventional cranes. Guideway cost would be kept low by the use of conventional box beams for the monorail, which minimizes the amount of materials required, and prefabrication, which minimizes expensive field construction. Disruptions to traffic and other activities would also be minimized, which would help to reduce local opposition to guideway construction.

Figure 3 shows a cross sectional view of the Maglev-2000 superconducting quadrupole. The 2 superconducting loops that form the quadrupole carry oppositely directed currents, with the separation

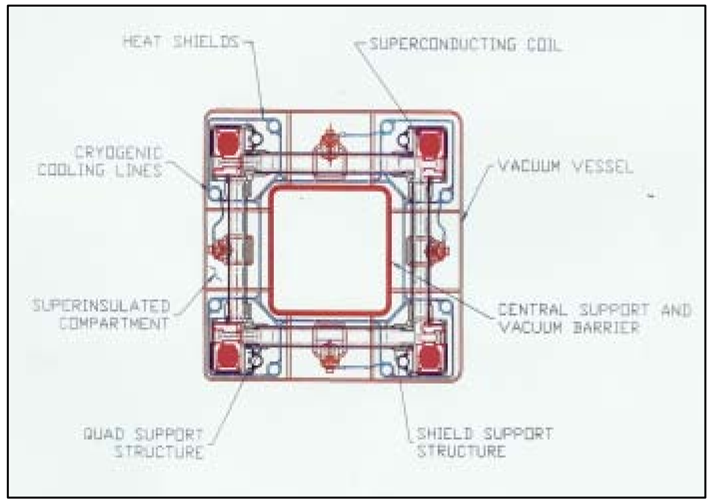

Figure 3 Superconducting Maglev-2000 Quadrupole Magnet Cross Section

between the loops equal to their width. The 2 loops can operate as separate circuits or be connected together into a single circuit.

The quadrupole has 4 magnetic poles that alternate in sign around its circumference. When used on a monorail guideway, the vertical side of a quadrupole interacts with the aluminum loops attached to the adjacent vertical side of the monorail guideway. When operating on a planar guideway (Figure 4), the bottom face of the quadrupole magnetically interacts with aluminum loops located on the guideway beneath the vehicle.

The ability to operate on a planar guideway as well as monorail also helps to reduce the construction cost of Maglev routes. When operating in densely populated urban and suburban areas,, the Maglev-2000 vehicles does not need to build a new, very expensive guideway with its accompanying disruptions and modifications to existing infrastructure. Instead, Maglev-2000 can transition

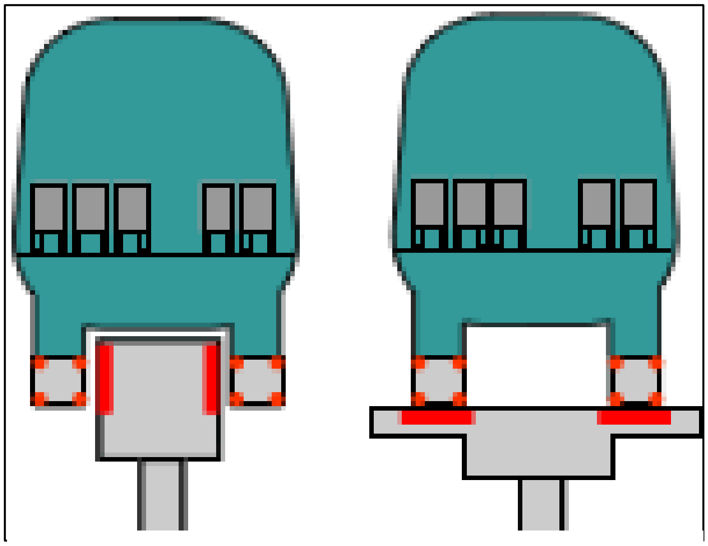

Figure 4 Maglev-2000 Vehicle on Monorail and Planar Guideways Using Quadrupole Magnets

to, and operate on, existing RR tracks to which aluminum loop guideway panels have been attached on the cross-ties (Figure 5). Conventional trains can continue to use the RR tracks, given appropriate scheduling. The cost of attaching guideway panels to enable levitated maglev-2000 operation is very small, only about 4 million dollars per mile, compared to the high cost of a new elevated guideway for Maglev

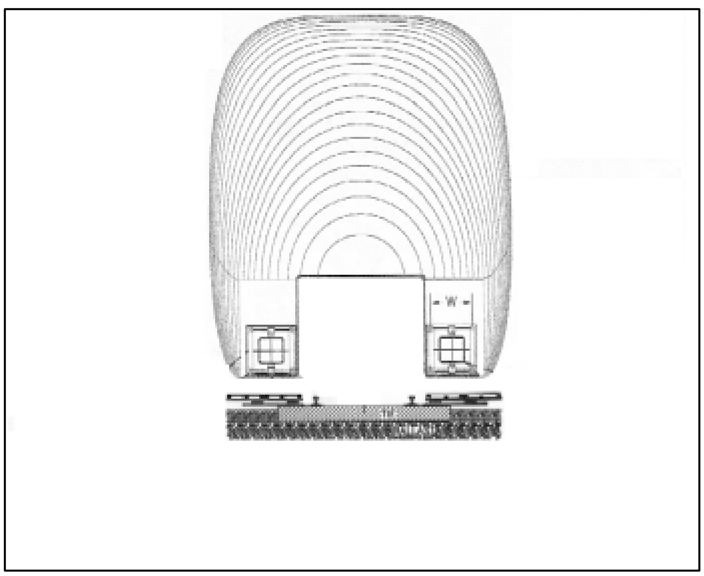

Figure 4 Drawing of Levitated maglev-2000 Vehicle Traveling on Conventional RR Tracks to Which Aluminum Loop Panels Have Been Attached to the Cross-Ties

systems that cannot operate on existing RR tracks.

Turning to the 2nd factor affecting Maglev implementation, revenues and net profits, the Maglev-2000 system is designed to carry trucks as well as passengers vehicles on its dual-use guideway. It accomplishes this because the powerful superconducting maglev-2000 quadrupoles can be located along the length of a Maglev vehicle without producing magnetic fields inside the vehicle that significantly exceed the natural Earth ambient value. This is a result of the considerably lower value of magnetic fringe fields from a quadrupole, compared to the dipole configuration used in the 1st generation superconducting Maglev system.

Figure 6 shows a drawing of a passenger Maglev-2000 and a truck carrying Maglev-2000 vehicle operating on the dual-use Maglev-2000 monorail guideway. The gross revenues from transporting 3000 trucks daily on a Maglev-2000 route (1/5th of the daily truck traffic on a typical Interstate

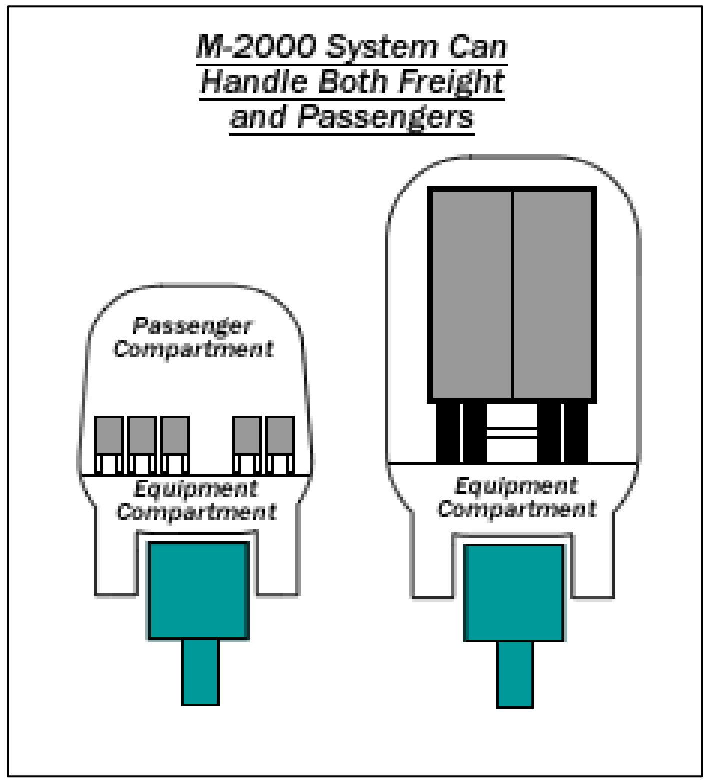

Figure 6 Maglev-2000 Passenger and Truck Carrier Vehicles on Dual-Use Guideway

Highway) are equivalent to 180,000 passengers per day, assuming a revenue of 30 cents a ton mile (typical U.S. outlay) for trucks, and 10 cents a passenger mile. The truck revenues alone would enable a payback time of less than 5 years for the Maglev-2000 guideway cost, an attractive opportunity for private investment.

The same Maglev-2000 guideway could also transport personal autos together with their passengers, offering travelers the opportunity to take their personal cars with them on long trips, at a lower cost than by highway. The Maglev-2000 system could also transport and deliver high value freight

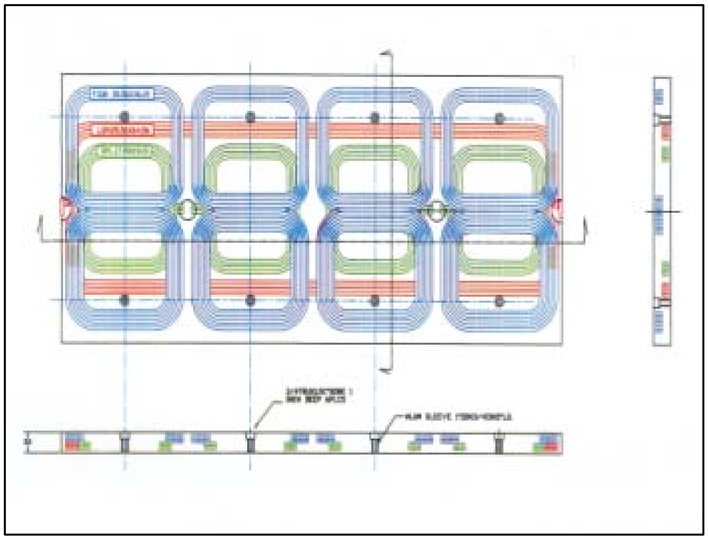

Figure 7. Drawing of aluminum loop guideway panel providing vertical lift and stability, lateral stability, and linear synchronous propulsion.

containers in a much shorter time than by conventional rail.

Truckers will find Maglev very attractive. A trucker could pick up a load at its origin, drive a few miles to the nearest Maglev station, travel across the U.S. in a few hours rather than a few days, and drive off the Maglev vehicle to deliver the load to its destination a few miles away. There would be much less wear and tear on the truck, and it could make 5 deliveries in the time it would take to go by highway.

The ability of M-2000 vehicles to travel on planar guideways also enables high speed electronic switching to off-line stations. This allows Maglev-2000 vehicles to by pass at high speed stations they are not scheduled to stop at, enabling stations to be closely spaced for convenient access, which increases revenue potential for the system, compared to having only a single or few stations in a given metropolitan area.

Figure 7 shows a drawing of the Maglev-2000 aluminum wire loop guideway panels. It has 3 sets of multi-turn aluminum loops: 1) a sequence of 4 short independent Figure of 8 loops; 2) a sequence of 4 short dipole loops; and 3) 1 long dipole loop.

When the panels are mounted on the vertical sides of the monorail guideway beam, the Figure of 8 loops provide levitation and vertical stability. The dipole loop on each side of the beam are connected together into a null flux circuit that maintains the vehicle in a centered position on the beam – when centered no current flows in the aluminum null flux circuit. When an external force (wind, curves, etc) acts to push the vehicles away from its centered position, a magnetic force develops that opposes the external force. The long dipole loop is part of the Linear Synchronous Motor (LSM) propulsion system, in which the loops on a sequence of panels are connected in series to form an energized block along which the Maglev vehicles travels. The energized block is typically on the order of 100 meters in length; as the vehicle leaves an energized block, its AC propulsion current is switched into the next block that the vehicle is entering.

For the planar guideway, the same panel design is used, with the panel laid flat on the planar surface beneath the line of quadrupoles on the moving vehicle. The Figure of 8 loops now provide lateral stability, generating magnetic restoring forces if an external force acts to displace the vehicle from its centered position on the guideway. The dipole loops act individually, with inductive currents that levitate and vertically stabilize the vehicle as it passes overhead. The LSM loops function in the same way as they do on the monorail guideway.

The planar guideway panel configuration can also be used to levitate and propel Maglev vehicles along existing RR tracks, with the panels attached to the cross-ties of the RR tracks.

The planar guideway is also used for high speed switching. At a switch section, there are two lines of overlapping guideway loops, which can be either electronically open circuited or closed circuited, depending on the desired switching action. Line A of guideway loops runs straight ahead on the main line, while the second line (Line B) of loops diverges laterally at a rate acceptable for passengers. If the loops in line A are close-circuited and those in Line B are open circuited, the vehicle travels straight ahead on the main route. If the reverse is used (Line A open, Line B closed), the vehicles diverges laterally from the main route onto a secondary guideway that leads to the off-line station. The high speed vehicle then decelerates on the secondary guideway that leads to the off-line station. When the vehicle leaves the station to rejoin the main line, it accelerates on an out-bound secondary guideway that leads to the switch section where the high speed vehicle re-enters the main line.

The next section of the paper describes the fabrication and testing of full scale Maglev-2000 components discussed above in order to determine their performance and validate the projections of their cost.

3. FABRICATION AND TESTING OF MAGLEV-2000 COMPONENTS

Figure 8. NbTi Superconductor Loop for Maglev-2000 Quadrupole

Figure 8 shows one of the two wound superconducting loops used for the Maglev-2000 quadrupole. The loop has 600 turns of NbTi superconducting wire, supplied by Supercon, Inc. of Shrewsbury, MA[14]. At the design current of 1000 Amps in the NbTi wire, the Maglev-2000 quadrupole has a total of 600,000 Amp turns in each of its 2 superconducting (SC) loops. The SC winding is porous, with small gaps between the NbTi wires to allow liquid Helium flow to maintain their temperature at 4.2 K, and to stabilize them against flux jumps and micro movements.

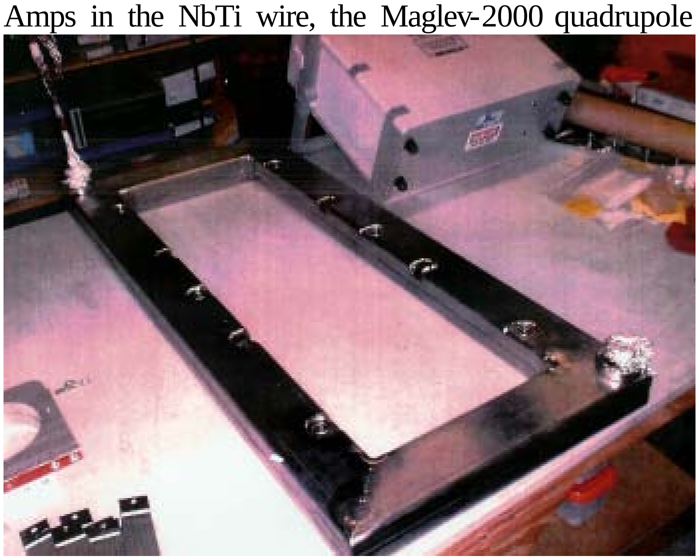

Figure 9. NbTi Superconducting Loop Enclosed in Stainless Steel Jacket

Figure 9 shows the SC loop enclosed in its stainless steel jacket. Liquid Helium flows into the jacket at one end and exits at the end diagonally across from the entrance providing continuous Helium flow through the SC winding. Before insertion of the SC loop into the jacket, it is wrapped with a thin sheet of high purity, aluminum (5000 residual resistance ratio) to shield the NbTi superconductor from external magnetic field fluctuations. After closing the jacket, a second layer of high purity aluminum is wrapped around it for additional shielding.

Figure 10 shows a CAD-CAM drawing of the complete Maglev-2000 cryostat that holds 2 superconducting quadrupoles. The magnetic polarity of the front SC quadrupole is opposite to that of the rear quadrupole. This allows levitation at lower speed than if the 2 quadrupoles had the same polarity, due to less L/R decay of the currents induced in the aluminum guideway loops. The 2 SC loops are supported by a graphite-epoxy composite structure that resists the magnetic forces – due both to the forces in a loop from its self current, and to the forces between the 2 loops – that act on them.

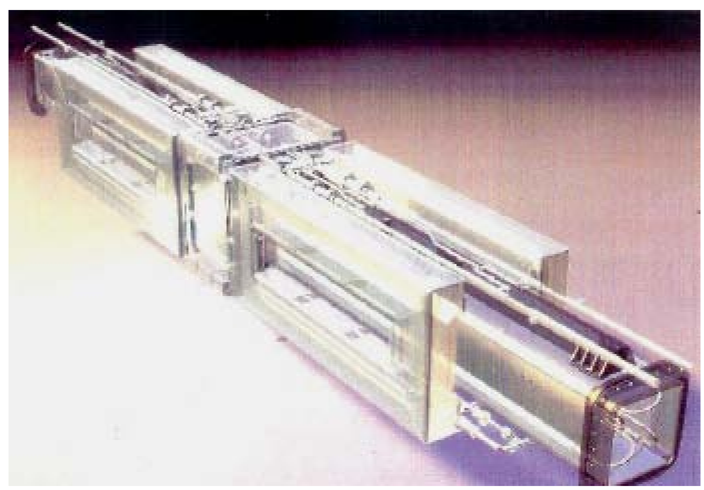

Figure 10. CAD-CAM Drawing of Maglev-2000 Superconducting Quadrupole

Figure 11 shows the SC loops, support structure, and cooling currents for the Maglev-2000 quadrupole being assembled in Maglev-2000's facility on Long Island. The SC loops have a 10 K thermal shield, which is cooled by Helium exiting from the jacket holding the SC loop. The SC quadrupole structure is then enclosed by an outer layer of multi-layer insulation (MLI) consisting of multiple alternating layers of glass fiber and aluminum foil. A second thermal shield encloses the SC quad, and maintained at ~70 K by the helium out-flow from the 10 K primary thermal shield.

Figure. 11 Assembly of Maglev-2000 Superconducting Quadrupole

Figure 12 shows the completed SC quadruple enclosed in its vacuum cryostat, while Figure 13 shows testing of the quadrupole magnetic levitation and propulsion forces using DC current in the aluminum loop guideway assembly beneath the quadrupole as a stand-in for the induced currents. The quadrupole was successfully tested to its full design current of 600,000 Amp turns. The magnetic forces between the quadrupole and the guideway loop assembly were measured as a function of vertical separation and lateral displacement from the centered position, and longitudinal position in the direction of movement along the guideway. The measured forces agreed with 3 D computer analyses.

After successful testing in Long Island, the SC

Figure 12. Completed Maglev-2000 Quadrupole Enclosed in its Cryostat

quadrupoles were shipped to Maglev-2000's facility in Titusville, Florida for a levitation test of the first end of the Maglev-2000 vehicle chassis.

Figure 13. Testing of Magnetic Forces on Maglev-2000 Quadrupole Using DC Current in Aluminum Loop Panel

Unfortunately, because the quadrupoles had been transported by commercial highway truck service without adequate protection against vibration and bumps on the trip (program funding was not adequate for air supported transport service) the cryostats developed some micro cracks at weld points in their cases. These microcracks degraded the thermal insulation performance by air in-leaks sufficiently that the operating temperature of the NbTi superconductor remained just above the transition point to the superconducting state. Program funding was not available to repair the microcracks and retest the quadrupoles on the Maglev-2000 vehicle.

In the time following the Maglev-2000 quadrupole tests, high temperature superconductors have become much more capable, and are being commercially produced in substantial amounts. Using YBCO high temperature superconductor wire , it appears very possible to fabricate Maglev-2000 quadrupoles that would be much simpler in construction, with much easier refrigeration requirements. The YBCO superconductor would operate at 65K with pumped liquid nitrogen coolant and a much simpler on-board cryocooler than would be required if NbTI superconductor at 4.2K were used. One Maglev-2000 quadrupole requires 3600 Kilo Amp turns of superconductor. At 10 per Kilo Amp meter, which appears achievable with large scale production of high temperature superconductor, the superconductor for it would cost $36,000. A passenger vehicle with 8 quadrupoles would then have a superconductor cost of $288,000, while a truck carrying vehicle with 16 quadrupoles would then have a superconductor cost of $576,000, both of which are very reasonable for a projected total cost of 5 million dollars per vehicle. Future tests of Maglev-2000 quadrupoles will probably involve high temperature superconductors with liquid nitrogen coolant, rather than NbTi superconductor with liquid Helium coolant.

As described in Section 2, the guideway loop panels (Figure 7) contain 3 sets of wound aluminum loops, composed of a set of 4 Figure of 8 loops, a set of 4 dipole loops, and 1 long LSM propulsion loop. Figure 14 shows a wound dipole loop, to be used in the panel. The aluminum conductor has a ~10 mil layer of nylon using a dip process to coat the conductor. The nylon insulation withstood 10 Kilovolt tests without breakdown. Figure 15 shows a completed guideway loop panel with all of its 9 loops.

Figure 14. Wound Dipole Loop for Guideway Panel Using Nylon Coated Aluminum Conductor

The completed panel is then enclosed in a polymer-concrete structure for handling and weather

Figure 15. Completed Guideway Panel with Figure of 8, Dipole, and LSM Propulsion Loops

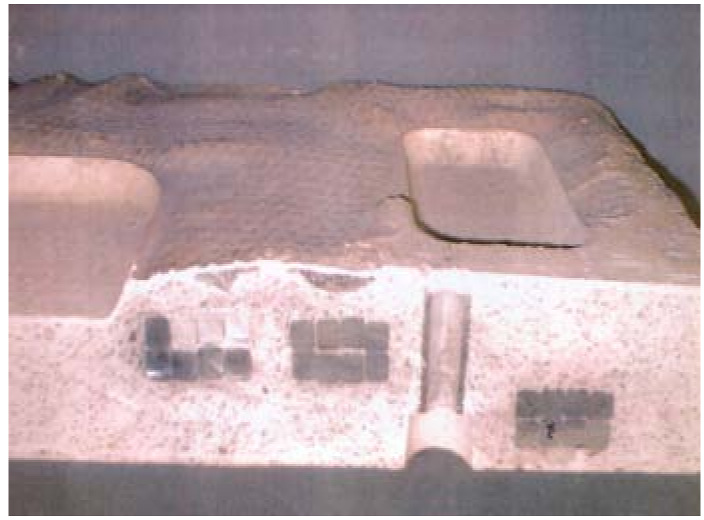

Figure 16. Guideway Loop Panel Enclosed in Polymer-Concrete Matrix

protection. (Figure 16) Polymer concrete – a mixture of aggregate, cement and plastic monomer – can be cast into virtually any form as a slurry. When the monomer polymerizes (the rate of polymerization is controlled by the amount of added promoter), the

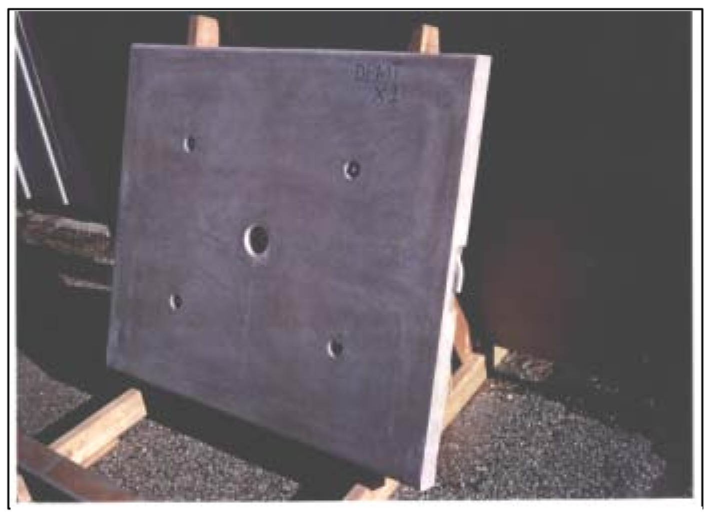

Figure 17. Polymer Concrete Panel with Enclosed Aluminum Loop Exposed for 2 Years to Outdoor Environment with Multiple Freeze-Thaw Cycles

resulting concrete-like structure is much stronger – a factor of 4 or greater – than ordinary concrete and not affected by freeze-thaw cycles, salt, etc. Figure 17 shows a completed polymer concrete panel left outside of the Long Island facility for 2 years. It was subjected to a wide range of weather conditions and multiple freeze-thaw cycles over the 2 year period, without any degradation.

After being fabricated at the Maglev factory, the guideway panels would be attached to the sides of the monorail or the surface of planar guideway beams to be shipped to a construction side for an elevated guideway, or transported to existing RR trackage that was to be modified for use by Maglev-2000 vehicles.

Based on fabrication experience at Maglev-2000's facilities on Long Island and Florida, using hand operated tooling, the 9 loops for a 2.2 meter long guideway panel can be fabricated in less than 1 week by one person. At $25 per hour, fabrication would then cost less than $1000 per loop. Per mile of 2-way guideway (2800) this amounts to less than 2.8 million dollars if made by hand. With automated tooling, the fabrication cost of the aluminum loops can be brought down considerably, to the order of 1 million dollars per mile. At $4 per kg for the aluminum conductor and $1 per kg for polymer concrete, the cost of the materials for the monorail guideway panels would be approximately 5 million dollars per 2-way mile.

Figure 18 shows the basic design for the monorail guideway beam. It is a hollow box beam made with

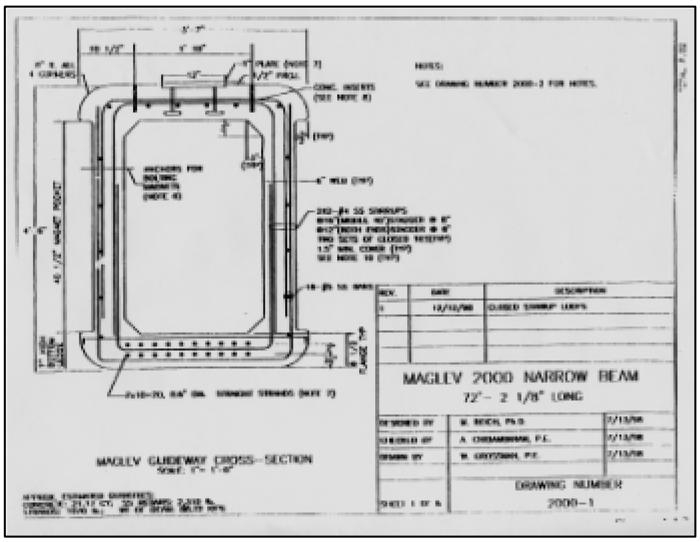

Figure 18. Design for 72 Foot Long Monorail Guideway Beam

reinforced concrete. Beam length is 22 meters and weight is 34,000 kg. It uses post tension construction, which allows the tensioning cables in the base of the beam to be re-tightened if some stretching were to occur. The beam is tensioned to have a 0.5 cm upwards camber at the midpoint of the beam when it is not carrying a Maglev vehicle. When the Maglev vehicle is on the beam, the beam flattens out to a straight line condition, with no vertical dip or camber along its length.

Figure 19 shows a photo of the fabricated beam after transport by highway truck from the manufacturing site in New Jersey to Maglev-2000's facility in Florida. No problems in transport by

Figure 19. Photo of 72 Foot Long Monorail Guideway Beam Delivered to Maglev-2000 Facility in Florida From Construction Site in New Jersey

highway were encountered. The first beam cost $45,000 with a projected large scale production cost of $25,000 per beam. Since 1999, construction costs have increased. At $50,000 in today's dollars, 140 beams for a 2 way monorail guideway would cost 7 million dollars per mile.

Figure 20 shows a CAD-CAM drawing of the aluminum chassis fabricated for a 20 meter long Maglev-2000 test vehicle, designed to carry 60

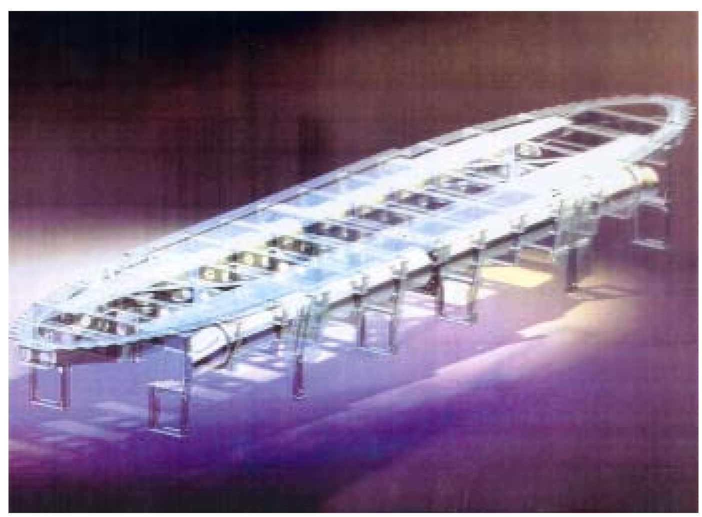

Figure 20. CAD-CAM Drawing of Aluminum Chassis for 60 foot Long Maaglev-2000 Vehicle

passengers in urban and suburban service. Figure 21 shows the fuselage for the test vehicle. If the Maglev-2000 Florida program had been down selected by the FRA, the assembled vehicle would have been tested on a short section of guideway. The Maglev-2000 components are presently in storage.

4. CONCLUSIONS

Fabrication and testing of the basic Maglev-2000 components – superconducting quadrupole magnets, aluminum loop guideway panels, monorail guideway beam, and vehicle body – have been successfully carried out. The next step for the development of the commercial 2nd generation Maglev-2000 system is to test operating vehicles on a guideway. A 3 phase program for these tests has been developed. In Phase 1, tests on a 0.5 mile guideway of a passenger type vehicle would be carried out, with maximum speeds of 60 mph. The guideway would include both monorail, planar, and RR track sections. In Phase 2, the guideway would be extended in length to ~4 miles, enabling high speed tests up to ~ 300 mph. Both truck carrier and passenger type vehicle would be tested in Phase 2. In Phase 3, a guideway of ~20 to 25 miles in length would be constructed, which would ultimately become a segment of a commercial Maglev-2000 route, on which long duration continued running tests could be carried out. The projected time for the proposed program is 5 years.

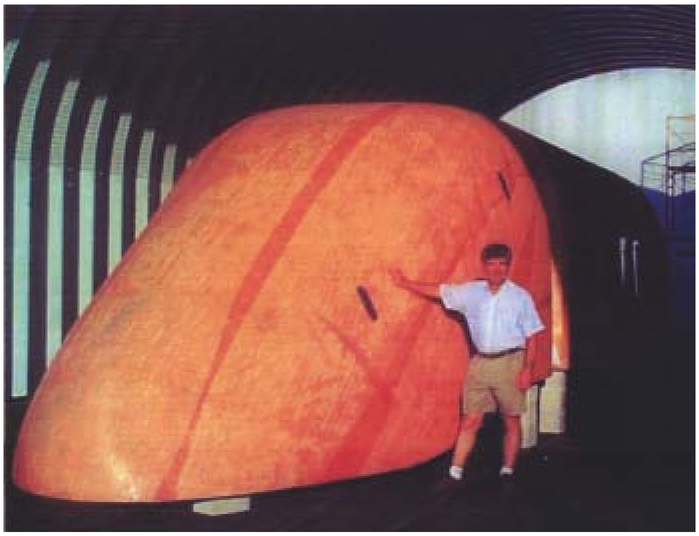

Figure 21. Photo of Fuselage for 60 Foot Long Maglev-2000 Vehicle

Maglev will inevitably become a major mode of transport in the coming decades, as World oil production peaks and then declines. Because it is electrically powered with the electricity coming from non-fossil power sources, it will help to reduce greenhouse gas emissions and global warming. As with all other previous transport technologies, its capabilities can evolve with time, resulting in lower costs and greater implementation. It is vital that this evolution proceed as rapidly as possible, due to the relatively short time that oil – the basis for virtually all of today's transport systems – will be available in sufficient amounts at affordable prices to maintain World economies.

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