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U.S. MAGLEV: STATUS AND OPPORTUNITIES

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Abstract – Recognizing the development of maglev systems in Germany and Japan, and the growing congestion, air pollution and energy consumption resulting from our current transportation system, the United States, in 1990, embarked on a program to evaluate the potential usefulness of these systems in the U.S. In this paper, the utility of maglev systems in alleviating some of these problems, progress in the current program, and opportunities for participation by the superconductivity and cryogenic communities are discussed.

I. INTRODUCTION

The maglev systems under development in Japan and Germany have frequently been discussed in the news media in recent years. The German Transrapid TR07 maglev system, comprising two articulated cars with a total length of 51 meters and a weight of 106 metric tons, is designed to carry 200 passengers at speeds of 500 km/hr (300 mph). The system uses computer-controlled, copper-wound, iron-cored electromagnets aboard the vehicle for levitation, guidance and propulsion. These electromagnets react against an iron-cored linear synchronous motor wound into the guideway for propulsion and levitation. The clearance between the on-board magnets and the guideway is only 8 mm, promoting a great deal of discussion regarding the operation of the system in icing conditions. This system will be installed in Orlando, Florida in 1997.

The system under development in Japan uses superconducting magnets on the vehicle which induce currents in electrically conducting coils in the guideway to achieve levitation and guidance [1], and interact with an air-cored linear synchronous motor in the guideway for propulsion. The current test vehicle is 22 meters long, weighs 17 metric tons and is designed to carry 44 passengers at 420 kph (250 mph). The magnets in this vehicle have a clearance of about 150 mm from the guideway. Both systems can accommodate more cars in trains for increased capacity.

Although the United States had an active maglev program in the 1970's, the program was terminated in early 1975. Little more occurred here until 1990 when the National Maglev Initiative (NMI) was established to evaluate the possibility of incorporating maglev systems in the U.S. transportation infrastructure. Mr. Robert Krick of the Federal Railroad Administration directs this joint program of the Federal Railroad Administration, the Corps of Engineers and the Department of Energy. A series of contracts was funded in 1991 for the study of basic maglev principles and the economic, environmental, civil engineering, operational, safety, and market implications of these systems. In addition, four contracts were funded to define new or improved maglev systems. These studies are, or soon will be, completed, and a recommended direction for a U.S. program will be made in March, 1993.

The Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 provided considerable additional impetus to the U.S. effort by establishing a "National Magnetic Levitation Prototype Development Program" and a National Maglev Joint Project Office. Cost-shared funding of $725 million was authorized for the six-year development of a full-scale prototype maglev system not less than 19 miles in length, incorporating a guideway switch, and interfacing with an existing mode of transportation. Of this sum, $500 million is authorized from the Highway Trust Fund and $225 million from general funds. $45 million is authorized for fiscal year 1993, with increasing amounts in later years. The act provides for a 12 month long first phase of the program in which preliminary system designs will be made by multiple contractors, followed by an 18 month long second phase in which selected concepts will be designed in detail. A single contractor is then to be selected to construct the prototype system. A "Maglev Development Task Force" under the direction of Mr. Albert Bertini of the Corps of Engineers is directing this task.

A U.S. maglev system might differ in many respects from those designed abroad, presenting the opportunity to begin with a "clean slate". The system definition contractors were presented with challenging goals - and they have met them. Their vehicles will accelerate faster than the TR07, will climb grades of 3.5% without slowing, and will climb 10% grades at reduced speeds. The latter feature provides the option of climbing over hills rather than tunneling through them. They were asked to negotiate curves with radii of curvature as short as 400 meters (for using maglev on the Interstate highway rights-of-way as authorized by Congress), and to produce designs that reduce the magnetic fields in the passenger compartments to levels that are or can be made to be compatible with any regulatory requirements. These specifications and goals have resulted in designs with "tilt bodies" to improve the comfort of passengers in tight turns, extended vehicles which, in some cases, provide greater distances between the passengers and superconducting magnets and innovative means of reducing magnetic fields. The resulting designs are currently heavier than one might wish, but they provide functional capabilities that are not present in the designs from abroad.

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II. THE NEED FOR MAGLEV

The U.S. transportation system is powered almost entirely by petroleum - consuming 63.7% of the 6.3 billion barrels of oil used in the country in 1989 [2]- 35% more than we produce domestically [3]. This depletes our supplies, increases our dependence on foreign producers, contributes to our negative balance of trade, and pollutes the air. Maglev, powered by electricity, can help since electricity can be generated by many alternative fuels producing less pollution. And since maglev is expected to operate over distances of 50 - 600 miles, it uses about one-third of the energy per passenger mile of aircraft and about one-half the energy of automobiles [4] (Fig. 1). This energy efficiency is accompanied by a disproportionately large reduction in the amount of pollution. And these pollutants are emitted only at the power plant where they are best controlled.

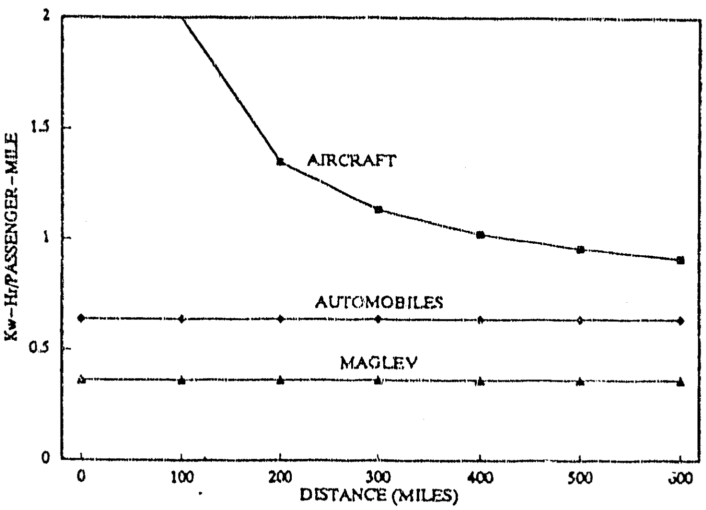

Figure 1. Modal energy use per passenger-mile by distance. Maglev: 156 seats, 60% load, Aircraft: 140 seats, 60% load, Auto: 1.83 passengers. Preliminary calculations of A. Vyas, D. Feber and L. Johnson, Argonne National Laboratory.

The air transportation system is becoming increasingly congested. The FAA listed 11 airports having 3 million or more passenger-hours of delays in 1989, and projected that 22 more will have equal or greater delays by 1996.[5] Maglev can replace many of the short-haul flights from these airports (which make up 50% or more of the flights at some airports). These are very energy intensive flights since much of their fuel is spent in taxing, take-off, and landing operations. Landing slots freed by maglev can be used for long-haul air operations which are faster and more energy efficient [5]. And because of the time consumed in these operations and the time required to load and unload the planes, the scheduled speeds of these aircraft are much lower than commonly realized (Fig. 2), making maglev speed-competitive over this range. In fact, for air operations entailing connecting flights, the average speed is frequently under 300 mph for trips exceeding 2000 miles. In addition to the time advantage, maglev is able to make stops at intermediate cities, providing a capability that

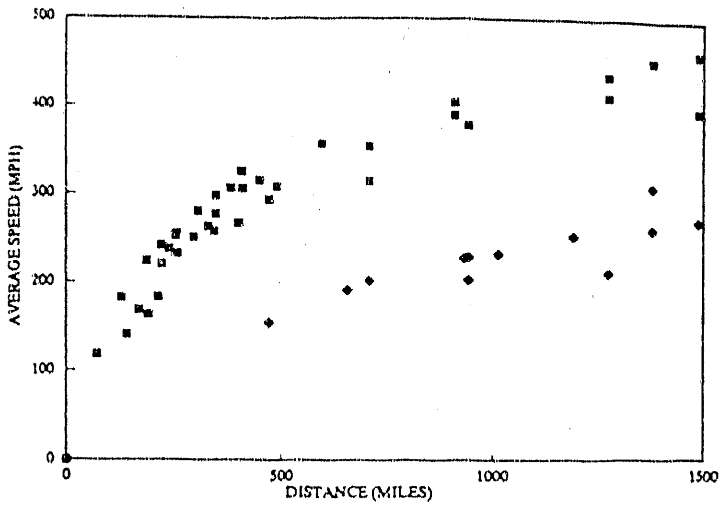

Figure 2. Average speed of scheduled airlines versus distance. Data from Official Airline Guide, June, 1992. Square symbols are direct flights, diamonds are flights with connections.

is not reasonably available with aircraft. And, the non-contact design and large clearance of many maglev systems assures that their operation will be less affected by rain, fog, ice and snow than will automobiles, airplanes and trains. Maglev systems will also provide large numbers of passenger-miles per hour of service. With 200 passenger vehicles departing at 2 minute intervals, the system can transport 6,000 passengers per hour in each direction, the equivalent of 15 - 400 passenger Boeing 747's in each direction. The maglev and aircraft will provide 1.8 and 3.0 million passenger-miles of service per hour respectively. Both numbers will be reduced by delays in stopping, but as already noted, maglev has a major advantage in speed in short-haul travel, and more vehicles can be linked in to increase the capacity by an additional factor of six or more. By comparison, a single freeway lane operating at 60 mph has a capacity of about 700 cars per hour (3,500 passengers per hour) and provides 210,000 passenger miles per hour of service [6], about six to twelve times less than a single maglev guideway.

For energy, environmental, travel time, and capacity reasons, maglev is superior to air travel for distances of less than 600 miles.

III. THE U.S. MAGLEV PROGRAM

The National Maglev Initiative has established a program office in the Federal Railroad Administration for pursuing its objective of assessing the potential of maglev in the U.S. The overall program is directed by the Federal Maglev Executive Committee (Table 1). The senior NMI staff is supported by Engineering, Economics and Support staffs at the same site. Additional support is provided by Corps of Engineers staff members at Huntsville, Alabama, Vicksburg, Mississippi, and Hanover, New Hampshire, and by Department of Energy Staff members at Argonne and Brookhaven National Laboratories, by the staff of Volpe National Trans-

Table 1. Federal Maglev Executive Committee

Administrator, Federal Railroad Administration
Asst. Secretary of the Army, Civil Works
Asst. Secty DOT, Policy and International Affairs
Asst. Secty DOE for Conservation and Renewable Energy
Deputy Assoc. Admin., Environmental Protection Agency
Administrator, Federal Highway Administration
Administrator, Federal Aviation Administration
Administrator, Urban Mass Transportation Administration
Administrator, DOT Research and Special Programs

portation Systems Center in Cambridge, Massachusetts and by consultants. This organization is responsible for the overall planning and execution of the current maglev program. The responsibilities include assessing research needed to reach the required decision point, and soliciting, funding and evaluating the work performed.

Any maglev system will be complex, entailing the design, construction, and operation of new power, propulsion, levitation, magnet, communication and control systems. A completed system will require the construction of perhaps thousands of miles of civil structures (guideways) and incorporating into them linear electric motors for propulsion, and wayside power conditioning and control systems. The vehicles must be designed and constructed. Each of these will have specialized features that will operate with all other components to provide safe, comfortable transportation in essentially all weather conditions. None has ever been constructed in the United States.

Safety, ride comfort, and economics will determine the acceptability of the ultimate system to the public. The ride comfort will depend on the electromagnetic suspension system and its dynamic interaction with a flexing guideway. These parameters must be assessed in the absence of significant numbers of persons who have traveled at these speeds in close proximity to the ground, and therefore in the absence of reliable data upon which the designs can be based.

The economics of the system must similarly be estimated if it is to operate in a competitive environment with other modes of transportation. Potential corridors, and networks of routes must be evaluated to estimate the potential ridership available in them and the feasibility of realizing a return on the money invested. The system cannot stand alone, however, and, to be acceptable, must interface with existing transportation modes to provide a service that is unavailable by other means. Reliable estimates of the cost of constructing and operating these systems are necessary. The guideway, as the single most costly part of the system, is of special concern.

The safety of maglev (as well as other high-speed rail systems) has been assigned to the Federal Railroad Administration and is being evaluated under the direction of Mr. Arne J. Bang. These assessments include experimental studies of the biological effects of magnetic fields being performed at Argonne National Laboratory.

Broad Agency Announcements. As a part of the task of assessing these concerns, Broad Agency Announcements were issued in 1990, soliciting proposals for research on topics related to magnetic levitation. Twenty-six projects, covering a very broad range of topics, have been completed under this program. Some of the basic considerations of magnetic suspension, guidance and propulsion were evaluated at the Charles Stark Draper Laboratories and at Kaman Science, Inc., MIT, and Babcock & Wilcox. Means of transferring power to the vehicle from the guideway for the on-board power requirements were explored by Foster-Miller Corporation. General Atomics studied advanced power conditioning technologies, and Intermagnetics General assessed superconducting linear induction motors. General Electric explored the use of shielded superconducting magnets, and the Plasma Fusion Center of MIT considered the uses of superconducting cables in closed conduits.

Many sensors will be used in an operating maglev system to determine the condition of the guideway, the presence of obstacles, and the location and velocities of the vehicles, among other factors. Means of enforcing the speed on the guideway were investigated by Battelle Memorial Institute. Martin Marietta studied the integrity, alignment, and right-of-way of the route, and other of these considerations were evaluated by Babcock & Wilcox, Corp. Aerodynamic interactions of the vehicle with the atmosphere and with the guideway were investigated by the Charles Stark Draper Laboratories, and the noise from vehicles was analyzed by Harris Miller Miller & Hanson, Inc. Matters of the dynamics, civil designs, thermal effects, and costs of the guideway were studied by Foster-Miller, MIT, Martin-Marietta and Parsons-Brinckerhoff. Intermodal station designs were considered by the University of Washington, and equipment required to operate maglev vehicles on existing rails near cities were explored by Parsons-Brinckerhoff. Procedures and plans for testing the maglev systems developed under this program were developed by Martin Marietta, the question of reliability of computerized controls was studied by the Charles Stark Draper Laboratories, and electromagnetic noise measurements were made on and around the TR07 system and analyzed by Electromagnetic Measurements and Analysis Corp.

These studies have had multiple effects. First, and perhaps foremost among them is the establishment of a cadre of personnel that is aware of and working on maglev problems. Solutions to technical, financial and logistical problems of the magnitude presented by this effort will not occur rapidly, but will evolve in concert with the changing requirements imposed by studies in related areas. Second, the significance of some of the more fundamental studies performed might not be recognized for some time to come. In fact, some of these ideas might not be applicable to maglev systems as they are currently conceived. These studies have not provided all the answers to our questions, but the level of understanding is very much greater than it was only a year ago.

System Concept Definition Studies. The centerpiece of the NMI funded program has been the work performed by four teams in developing new maglev system concepts. These teams are led by Bechtel National Corporation, Grumman

Corporation, Magneplane International Corporation and Foster-Miller, Inc.

The Bechtel team includes Hughes Electronics, the Electro-Motive Division of General Motors, the Massachusetts Institute of Technology, and Charles Stark Draper Laboratory.

The Grumman team includes Parsons Brinkerhoff, Intermagnetics General, Gibbs & Hill, Battelle Memorial Institute, PSM Technologies and the New York State Institute on Superconductivity.

The Foster-Miller team includes the Boeing Corporation, General Atomics, General Dynamics, Parsons-DeLeuw and Morrison-Knudsen.

The Magneplane International team include the MIT Plasma Fusion Center and Lincoln Laboratory, Raytheon Equipment Division, United Engineers, Beech Aircraft, Process Systems International, Failure Analysis Associates, and Bromwell & Carrier.

Each team has generated a conceptual design of a complete maglev system and has analyzed in detail the performance of their system. These designs include all parts of the systems, including:

- Levitation and Guidance
- Propulsion
- Power, Power Conversion and Control
- Guideway
- Vehicle
- Communications
- Control

Analyses have been made of:

- Aerodynamics Effects
- Utility Power Supplies
- Environmental Effects (Noise, Magnetic Fields etc.)
- Ride Quality
- Vehicle-Guideway Dynamic Interactions
- Performance (acceleration, cornering, energy usage)
- System Implementation
- Safety
- Costs.

The results of these studies have not been released and cannot be described in detail for proprietary reasons. Of interest to this conference, however, is the fact that each of the concepts uses superconducting magnets in their levitation, guidance and propulsion systems. Two of the systems are similar in concept to the current Japanese and German systems but make important changes in them.

The Grumman system is analogous to the TR07 maglev system in Germany in that it uses iron-cored magnets on the vehicle and an iron-cored linear synchronous motor (LSM). Unlike the TR07, however, the LSM is mounted on the guideway at an angle to the vertical direction so a single set of magnets provides lift, guidance and propulsion forces. A 5 cm air gap, much larger than that of the TR07, is achieved by using superconducting magnets to provide the electromotive force for the iron-cored magnets. (Patents have been applied for on this system, and presumably on all the other systems). Like the TR07, the magnets are actively controlled and are expected to provide adequate ride quality without the use of a secondary suspension system.

The Magneplane design extends the work done in the 1970's by members of this group and uses superconducting magnets on the vehicle and a continuous conducting sheet in the guideway. The guideway is shaped as a "trough" and permits the vehicle to bank as it turns corners, simplifying the achievement of passenger comfort in sharp turns. Propulsion is provided by an air-cored linear synchronous motor in the guideway.

The Bechtel concept uses superconducting magnets distributed along the bottom of the vehicle and a "ladder track" concept to achieve suspension and guidance. Propulsion is again provided by the interaction of on-board magnets with air-cored linear synchronous motor windings in the guideway. A simple box-beam guideway design is incorporated in the concept.

The Foster-Miller concept also uses superconducting magnets on the vehicle which interact with coils mounted in the guideway for levitation and propulsion. The guideway is in an open form that reduces the collection of snow and water and is designed to be manufactured of prestressed concrete with the coils in place and installed on site. Some non-magnetic, non-conducting fiber reinforcing is used in the guideway in regions of high fields. The linear synchronous motor is unique in that it is locally commutated, applying power only in the vicinity of the vehicle rather than to a complete block. This concept is expected to improve the efficiency of the motor. A high speed switch with no moving parts is also unique to this system.

These concept designs represent the most thorough analyses of maglev technologies that have been made in the United States and will provide a solid basis for future decisions regarding the role the U.S. should play in maglev technology.

In-House Efforts. The government, as the buyer of these research efforts, is placed in the postion of determining what research should be done and evaluating the ultimate results. In other words, the government must be a "smart buyer". The government was faced with the dilemma that it, like U.S. industry, had not been involved in maglev technologies since 1975, and was in no better postion to recommend or evaluate them than was industry. For this reason, considerable efforts were made to establish a group of technically competent personnel within the government. Those few people who previously worked in the field and were available for this purpose have largely been assimilated into the effort.

Dr. John Harding, who was associated with the FRA's maglev program in the 1970's, serves as chief scientist of the NMI, and Mr. Arrigo Mongini of the FRA is leading the market and economic analyses. Dr. Thomas Comparato of the Volpe National Transportation Center directs work on magnetic and propulsion studies, market and economic analysis, costing, performance, safety, ride comfort and other activities at that center. Mr. Patrick Sutton, Assistant Director of the NMI leads the DOE efforts. Dr. Larry Johnson, who became involved with studies of maglev as a result of evaluating uses of HTSC's, and Dr. Donald Rote with previous experience with magnetic levitation melting of metals, and the author, direct the work at Argonne National Laboratory where experimental measurements of magnetic forces on magnets and moving guideways, the development of computer codes, and market and economic analyses are being performed. A large and enthusiastic group of engineers and managers has been enlisted from the Corps of Engineers, led by Mr. Stu Kissinger, the Deputy Director of the NMI. The Corps provides experienced designers and managers of large scale civil structures and engineering projects as well as seasoned cost estimation talents. In addition to these primary personnel, expertise has been provided by Brookhaven National Laboratory in superconducting magnets and cryogenics, NASA in aerodynamic studies, the Environmental Protection Agency in environmental considerations, and other governmental entities as required.

These personnel are responsible for the planning, program management, technical support, and contract evaluations of the NMI program.

IV THE ISTEA PROGRAM

Whereas the NMI program has the responsibility of assessing the potential for maglev in the United States and for recommending future courses of action, the ISTEA act authorizes the design and construction of a full-scale prototype system, not less than 19 miles in length, to be used to evaluate the selected maglev technology and the public's response to it. The prototype system is to include at least one switch and to interface with an existing mode of transportation. The legislation specifies that the prototype system be designed and constructed within six years, with requests for proposals for the first phase of the program to be issued in early FY 1993. This is a very tight schedule, and Congress will probably be asked to delay the program while the results of the current NMI program are evaluated. Accordingly, the administration did not include the program in the budget for fiscal year 1993.

Although the program is not in the budget for 1993, the Corps of Engineers and the FRA have established a "Maglev Development Task Force" under the direction of Mr. Albert Bertini of the Corps, with the assistance of Mr. Larry Blow of ANL, to develop specifications and requirements for the system and to evaluate strategies for implementing the program. This Task Force, which reports to the Federal Maglev Executive Committee, will assess the characteristics required of the prototype system, the research and development needed to develop a system, and means of implementing the program. It should be recognized that this is a major task in that the system will be expensive and physically large, requiring considerable management and procedures for selecting one of the many possible sites for the system.

The results from the NMI and the "Task Force", the formal establishment of the National Maglev Joint Project Office, as well as a determination of how and when to proceed with the development of the Prototype Maglev System can be anticipated in 1993. Many opportunities for research and development including the cryogenic and superconductivity communities will open in the next year.

V. OPPORTUNITIES

The development of maglev like any new system presents opportunities for innovation. As discussed above, many new concepts and ideas have been developed in the past year, and others can be expected.

Superconducting magnets for maglev provide the levitation and guidance for the vehicle and must therefor be reliable, or redundancy must be provided that will permit safe operation in the event of a failure. Most magnet designs are predicated on the assumption that the magnet must survive a quench. For maglev, this assumption is insufficient.

One anticipated source of magnet quenches in a maglev system is the loss of coolant due to the failure of a cryostat due to fatigue failure or collision with debris on the guideway. Means for reducing or delaying the effects of losing the vacuum or the cryogen would allow the vehicle the seconds it requires for a safe stop. Another source could be failure of the structural members of the support system. Much attention has been paid to this concern for years by the cryogenic community, but seldom in applications that are so weight and safety sensitive.

Ac losses in the cryostat result from the vibration of the vehicle as it passes over the uneven guideway to which is is inductively coupled. This leads to increased refrigeration or storage requirements. Designs of magnets, cryostats and shields that minimize these effects would be welcome. In doing so, however, it is important to see that the resulting heat load is not simply transferred from a metal sheet at room temperature to the magnet at helium temperature where the cooling requirements are orders of magnitude more difficult.

The current densities and magnetic fields required in some maglev systems are sufficiently low that high temperature superconductor can begin to be considered for this application. For the next few years, such magnets could be considered on an experimental basis, but then they must demonstrate the reliability, safety, and cost effectiveness of a passenger carrying transportation system.

Cooling of the magnets can be achieved by batch cooling or by on-board liquifiers. Liquifiers of the size, efficiency, ruggedness, and reliability required for this application are under development in Japan, but have not been built in the United States. An opportunity is presented by the absence of such refrigerators. Batch cooling has the advantage of efficiency of liquifaction in a large plant, but requires an unusual skill for transportation workers. The higher the skill level required, the more costly will be the operation of the system.

Shielding of the passenger from magnetic fields is required, but the level of shielding has not been determined. Innovative designs of the levitation systems that provide the necessary levitation and propulsion with minimal electromagnetic drag while having fields that decrease rapidly with distance have been found by the system concept contractors. Other designs might be conceived with sufficient thought. Some fields will necessarily exist at a distance from these magnet assemblies, however, and additional means might be required to reduce them. Ferromagnetic materials are of course an option, but add considerable weight to the vehicle. Conventional, distributed windings could also be used, but will require considerable amounts of on-board power. All of this suggests that high temperature superconductors might be used to provide low level shielding with minimal refrigeration requirements and needs to be explored in some detail.

As more consideration is given to maglev systems, more problems will occur and the opportunity for more research, development and innovation will arise. This community has contributed greatly to the endeavor to develop a new, environmentally benign, energy efficient, cost effective, high-speed transportation system for the 21st century. Your participation is still needed.

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